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Investigation of Flow Rate Calibration Procedures Associated with the High Volume Method for Determination of Suspended Particulates

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16. ABSTRACT

Determination of total suspended particulate (TSP) in the ambient air by the high-volume method requires three independent measurements, mass of particulate collected, sampling flow rate, and sampling time. Several potential sources of error in each of the three above measurements have been identified. Implementation of technically sound, standardized flow rate calibration has long been recognized as one of the most effective means of improving the accuracy and precision of TSP data. Procedures for accomplishing this have not been standardized.

The purpose of this project was to investigate potential sources of error in the flow rate calibration used in making TSP measurements using the EPA reference method. The first task was a theoretical study of the flow rate calibration and measurement techniques applicable to the high-volume sampler, and secondly to design and carry out an experimental program to assess the validity of the theoretical study concerning temperature and pressure corrections for calibration and use of the high-volume sampler. The indications from this study are that to comply with EPA's requirement that all ambient air quality data be referenced to standard conditions of 298°K (25°C) and 760 mm Hg and to increase the comparability of TSP data, the flow rate should be based on the flow rate of a standard volume and reported as mass/std volume, e.g., g/SCM. This procedure would require that ambient temperature and barometric pressure at the time of sample collection be known in order to calculate the flow rate based on standard volume.

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Investigation of Flow Rate Calibration Procedures Associated with the High Volume Method for Determination of Suspended Particulates

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June 1978

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ABSTRACT

An engineering study and experimental evaluation were made of the flow rate calibration and measurement procedures applicable to the high volume method of measuring total suspended particulates in ambient air. Primary emphasis was directed toward identification and evaluation of technically sound procedures for including temperature and pressure correction techniques in the calibration and measurement procedures.

Three measures of flow rate are discussed. Flow rate calibration and measurement procedures are recommended. Experimental data of high volume sampler calibrations performed at different pressure and temperature combinations ranging from about 560 to 760 mmHg and 10° to 40°C are included.

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RTI hereby acknowledges its thanks to the above-mentioned individuals for their efforts in bringing this project to a successful conclusion.

SYMBOLS AND NOMENCLATURE

Symbols that are used throughout the report and their definitions are given here. Those symbols used only in one section of the report are defined when they are used. Subscripts and/or superscripts are employed to differentiate between specific situations.

ΔH = Pressure drop across the secondary calibration device (i.e., orifice calibration unit or reference flow device), in.H_2O.

I = Rotameter reading, arbitrary.

PT = Pressure transducer reading, arbitrary

P_b = Barometric pressure as read from a barometer, mmHg.

P_{std} = Standard absolute pressure, 760 mmHg (29.92 in. Hg).

ΔP = Pressure drop between atmospheric and inlet of the Roots meter, mmHg

$Q_{theoretical}$ = Flow rate that would occur at standard reference conditions of 298 K (25°C) and 760 mmHg for a specific pressure indication (ΔH or I) observed at any temperature and pressure, $a_1 (\Delta H)^{1/2}$ for secondary calibration device, $c_1 I + d_1$ for high volume sampler, where constants a_1, c_1 (slopes) and d_1 (intercept) are determined from experimental data (this measure of flow rate is frequently labeled as a "reference flow" in the literature).

Q_{std} = The rate of flow of a standard volume, $a_2[(\Delta H)P_b/T_a]^{1/2}$ for secondary calibration device, $c_2 I (P_b/T_a)^{1/2} + d_2$ for high volume sampler, where constants a_2, c_2 (slopes) and d_2 (intercept) are determined from experimental data. (If expressed in English units, Q_{std} is often symbolized by SCFM in the literature.)

Q_a = Flow rate at ambient conditions, $a_3[(\Delta H)T_a/P_b]^{1/2}$ for secondary calibration device, $c_3 I (T_a/P_b)^{1/2} + d_3$ for high volume sampler, where constants a_3, c_3 (slopes) and d_3 (intercept) are determined from experimental data.

STP = Standard temperature (298 K) and pressure (760 mmHg) conditions.

TSP = Total suspended particulates, $\mu g/m^3$.

T_a = Ambient temperature, K.

T_{std} = Standard temperature, 298 K (25°C).

t = Time required to pass air volume V_m through the Roots meter, minutes.

V_m = Volume of air measured by the Roots meter at meter conditions, m^3.

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Section 1
INTRODUCTION

Determination of total suspended particulate (TSP) in ambient air by the high volume method (1) requires three independent measurements, namely mass of particulates collected on the filter, sampling flow rate, and sampling time. Several potential sources of error in each of the three above measurements have been identified and discussed in the literature (2-5). Implementation of technically sound, standardized flow rate calibration and measurement procedures has long been recognized as one of the most effective means of improving the accuracy and precision of TSP data. In particular, the U.S. Environmental Protection Agency (EPA) requires that all ambient air quality data be referenced to standard conditions of 298 K (25°C) and 760 mmHg (6). Procedures for accomplishing this have not been standardized, and in actual practice attempts to comply with the requirement are made by including certain temperature and pressure corrections in the flow rate calibration procedures. Quite frequently, the techniques used do not accomplish the desired results and in some instances yield erroneous results.

The purpose of this project was to investigate potential sources of error in the flow rate calibration and measurement procedures used in making TSP measurements using the EPA reference method. Specific objectives of this project were:

1. To investigate the adequacy of the presently used procedures for making temperature and pressure corrections for flow rate measurements in the field where temperature and pressure conditions differ from calibration conditions;
2. To develop and evaluate improved procedures for correcting the flow measurements should the potential error of presently used procedures prove to be of significant magnitude; and
3. To prepare guidelines for high volume sampler flow rate calibration and data reporting procedures.

In the process of conducting a test program to accomplish the above objectives, sufficient experimental data were generated, in addition, to allow for:

1. A quantitative comparison of two different secondary calibration devices, i.e., the orifice calibration unit specified in the reference method and the reference flow (ReF) device being used by the Quality Assurance Branch (QAB) of the Environmental Monitoring and Support Laboratory (EMSL) as a mailable device for auditing high volume sampler flow rates; and
2. A comparison of primary calibrations of the two secondary calibration devices performed at different locations having significantly different atmospheric pressures.

This project was carried out as three tasks. The first task involved a theoretical study of the flow rate calibration and measurement techniques applicable to the high volume sampler. In essence, this first task was used to identify the points in the calibration and measurement process that required experimental verification. Task 1 of this project is discussed in Section 3 of this report. Specific topics include:

1. Physical principles of the high volume sampler;
2. Principles of fluid motion applicable to the high volume sampler;
3. Calibration of the secondary standard, i.e., the orifice calibration unit;
4. Calibration of the flow indicator, i.e., the rotameter or pressure transducer; and
5. Summary of calibration and conversion formulas.

Task 2 of this study is discussed in Section 4. The section describes the experimental program designed and carried out to assess the validity of the assumptions made and the procedures specified in Section 3 concerning temperature and pressure corrections for calibration and use of the high volume sampler. To characterize the influence of temperature and pressure, the experimental program included performing high volume sampler calibrations at four different atmospheric pressures ranging from approximately 763 mmHg down to 595 mmHg. At each of the four atmospheric pressures, the samplers were calibrated at four different ambient temperature levels. These levels were approximately 10°, 20°, 30°, and 40°C. Also, primary calibrations of the orifice calibration unit and the ReF device were made in the EMSL-RTP facility and in the EPA Region VIII facilities in Denver, Colorado. Two types of high volume samplers were tested. The first type consisted of a multihole exhaust base plate with a rotameter. The second sampler type had a single-hole exhaust orifice and used a pressure transducer. The section includes the conclusions reached regarding procedures for making pressure and temperature corrections based on results of the experimental data.

Task 3 involved the preparation of recommended calibration and data reporting procedures for the high volume sampling method based on results from the first two tasks. Step-by-step calibration and data reporting procedures are given in Section 5. Example treatment of calibration data, using the recommended procedures, is also included.

SECTION 2
SUMMARY AND RECOMMENDATIONS

SUMMARY

Results as they apply to the individual project objectives listed in Section 1 are summarized below.

1. A limited study of and familiarity with flow rate calibration and measurement procedures being used by different organizations engaged in high volume sampling indicates that several different procedures are presently in use. The greatest potential source of error appears to be in confusing and thus mixing different measures of flow rate. Two common occurances are:

    a. The high volume sampler is calibrated in terms of a flow rate standardized to standard reference conditions (this measure of flow rate is defined as $Q_{theoretical}$ in this document) versus the flow measuring device indication. This measure of flow rate ($Q_{theoretical}$) is frequently incorrectly reported as std m^3/min or std ft^3/min., a measure defined as Q_{std} in this document. The relationship between the two measures of flow rate is given by Equation (5) below. As an example, the magnitude of error that would result if $Q_{theoretical}$ representing the flow rate standardized to 25°C and 760 mmHg at the time of calibration is reported as Q_{std} for future field measurements made at 40°C (104°F) and 600 mmHg is calculated to be 13 percent by Equation (5) as follows:

    $$Q_{std} = Q_{theoretical}[(600/313)(298/760)]^{1/2}$$
    $$Q_{std} = 0.87\ Q_{theoretical}\ .$$

    As seen from Equacion (5) the greater the field conditions vary from standard conditions, the greater the error will be.

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b. The ambient flow rate indicated by the orifice calibration unit at the time of the sampler calibration is correctly converted to the flow rate based on a volume at standard reference conditions (Q_{std}) but then is incorrectly graphed versus or regressed on $I\ (T_a/P_b)^{1/2}$ rather than $I\ (P_b/T_a)^{1/2}$ as it should be, where I is the indication of the flow measuring device on the sampler. As in (a) above, the error in the reported flow rates from this incorrect procedure increases as the difference in field conditions and standard reference conditions increases. If the calibration is performed at near standard conditions, the above mistake results in reporting the actual flow rate (Q_a) at field conditions as the flow based on a volume at standard conditions (Q_{std}). Utilizing Equation (6) below and the same example temperature and pressure conditions as in (a) above shows that a 25 percent error would result if Q_a were reported as Q_{std} as follows:

$$Q_{std} = Q_a\ [(600/313)(298/760)]$$

$$Q_{std} = 0.75\ Q_a\ .$$

2. One of the primary objectives of this project was to evaluate temperature and pressure correction procedures applicable to high sampler flow rate calibrations and measurements. Based on the theoretical study of the high volume sampler (Section 3) and the results of the experimental program (Section 4), it is concluded that the following models, with the constants properly quantified through calibration, accurately predict the respective measures of flow rate over the ranges of temperature and pressure normally encountered in field sampling programs.

$$Q_{theoretical} = c_1\ I + d_1\ , \qquad (1)$$

$$Q_{std} = c_2\ I\ (P_b/T_a)^{1/2} + d_2\ , \text{ and} \qquad (2)$$

$$Q_a = c_3\ I\ (T_a/P_b)^{1/2} + d_3\ . \qquad (3)$$

Also, the three measures of flow rate are related in the following manner:

$$Q_{std} = Q_{theoretical}\,[(P_b/T_a)(T_{std}/P_{std})]^{1/2} \qquad (5)$$

$$Q_{std} = Q_a\,(P_b/T_a)(T_{std}/P_{std}) \qquad (6)$$

where

Q_a = actual flow rate at ambient conditions, m^3/min

$Q_{theoretical}$ = flow rate that would occur at STP conditions for a specified flow rate indication I (or PT) observed at ambient conditions, std (m^3/min)

Q_{std} = flow rate based on standard volume at STP conditions, (std m^3)/min

I = Rotameter indication (replaced by PT for the the pressure transducer), arbitrary

P_b = barometric pressure, mmHg

P_{std} = standard pressure, defined as 760 mmHg

T_a = absolute ambient temperature, K

T_{std} = absolute ambient temperature, defined as 298 K

c_1, c_2, c_3, and

d_1, d_2, d_3 = regression coefficients.

3. Attempts to incorporate the temperature of the air at the sampler exhaust into the flow rate correction procedure appeared to slightly improve data quality for the sampler equipped with a rotameter but had no noticeable effect on the sampler equipped with a pressure transducer.

4. An evaluation of the influence of relative humidity on the recommended flow rate calibration and measurement procedures showed that only at extreme conditions of low pressure (<600 mmHg) and high temperature (>40°C) would the resulting error in flow rate approach 2 percent if the density of dry air was assumed. Based on this analysis relative humidity corrections are not recommended.

5. Comparison of two secondary calibration devices, i.e., the orifice calibration unit and the ReF device, differing significantly in design, showed the ReF device to be slightly negatively biased with respect to the orifice calibration unit across all of the temperature and pressure combinations tested.

6. Primary calibrations of an orifice calibration unit and a ReF device performed in the EPA Region VIII facility in Denver, Colorado and repeated in the EMSL-RTP facility using different primary standards showed excellent agreement, when temperature and pressure corrections were made using models similar to (1), (2), and (3) above replacing I with $(\Delta H)^{1/2}$.

RECOMMENDATIONS

The first recommendation concerns the use of a common measure of flow rate for all TSP data, to comply with EPA's requirement that all ambient air quality data be referenced to standard conditions of 298 K (25°C) and 760 mmHg (6) and to increase the comparability of TSP data across organizations, projects, and geographical areas, it is recommended that all TSP data be based on the flow rate of a standard volume (Q_{std}) and reported as mass/std volume, (e.g., μg/std m^3). This procedure requires that ambient temperature and barometric pressure at the time of sample collection be known in order to calculate the flow rate based on a standard volume. Recommended procedures for determining or estimating these values are as follows:

1. On-Site Ambient Temperature Determinations — An accurate estimate of the average temperature for a 24-hour sampling period is difficult to obtain without a continuous recorder. Recommended procedures that would probably yield acceptable estimates, listed in order of preference, include but are not limited to:

   a. For sites close to or as a part of an air quality monitoring station equipped to monitor ambient temperature, the average temperature for the day recorded by the station's temperature sensor should be used for the average temperature for the high volume sampling period.

b. For high volume sampling sites visited daily, a mini-max thermometer giving the minimum and maximum temperature occurring since the last reset could be located on-site, and the average of the two extremes used for the sampling period average.

c. For sites not too far removed from a weather station and having about the same degree of exposure as the weather station, the average daily temperature as recorded by the weather station would provide an adequate estimate of the average sampling period temperature.

2. On-Site Barometric Pressure Determinations — For a fixed site the barometric pressure seldom deviates more than ± 5 percent from the average value. Therefore, an acceptable measure of barometric pressure for a given site can be obtained if the site elevation is known by making an elevation correction of approximately -23 mmHg (from sea level 760 mmHg) for each 30.5 m (1000 ft) above sea level. Barometric pressure for the site can then be treated as a constant.

The second recommendation concerns the high volume sampler configuration. As presently configured in the reference method the sampler utilizes a flow sensing device located downstream from the motor to measure flow rate. The design of this system requires that the sampler be recalibrated whenever maintenance is performed on the motor. It is recommended that a procedure allowing for the flow indicator to be located forward of the sampler motor be investigated. One approach could be to use a pressure gage with the natural venturi effect of the sampler throat. This would make the sampler calibration insensitive to motor conditions and may significantly reduce the required frequency of calibration depending upon the type of pressure gage employed.

SECTION 3

THEORETICAL DISCUSSION OF THE HIGH VOLUME SAMPLER

GENERAL

The objective of this section is to give an overview of the theory of the operation and the calibration of a high volume sampler. Specifically, the theory as presented in this section serves as the basis for the experimental program discussed in Section 4.

Flow rate measurement and calibration associated with the high volume method are complex and easily misapplied. This section covers the three measures of flow rate commonly used in practice and attempts to point out the misconceptions and errors most commonly encountered in field sampling.

Topics addressed in this section and the order in which they are discussed are as follows:

1. Physical principles of the high volume sampler,
2. Principles of fluid motion applicable to the high volume sampler,
3. Calibration of the secondary standards, e.g., the orifice calibration unit,
4. Calibration of the flow indicators on high volume samplers, and
5. Summary of calibration and conversion formulas.

THE PHYSICAL PRINCIPLES OF THE HIGH VOLUME SAMPLER

The high volume sampler is essentially a device that pulls a sample of ambient air through a filter within a measured time interval. Gravimetric analysis of the filter content, the measured rate of air flow, and the sampling time are used to determine the concentration of particulates in the air. Thus, three independent determinations are made -- the pollutant mass, the volume flow rate, and the sampling time. All three must be accurate to have an accurate concentration determination. The principles of the flow measurement devices incorporated in the high volume sampler are discussed in this section.

A functional schematic of the high volume sampler flow measurement system is shown in Figure 1. Air is pulled through the filter by a blower and passes along the windings of the blower motor and finally into a plenum within the motor housing just aft of the motor unit. The air in this chamber is then exhausted to the atmosphere through holes in the base plate of the motor housing. The base plate, in essence, functions as an orifice and thus allows a flow rate determination directly through the measurement of the excess pressure above atmospheric in the plenum. Since the base plate orifice is simply a flow constriction rather than a standard designed orifice meter, it is expected that it should require calibration. Some type of gage or transducer is obviously required to determine the excess pressure within the plenum and, in high volume sampler applications for this study, this is accomplished using a standard mechanical pressure transducer or a ball-in-tube rotameter. In the former case a single hole base plate is used, while in the latter case a multihole exhaust assembly is used. The mechanical pressure transducer draws no air from the plenum, while the rotameter indicator must extract a very small sample flow rate to provide its pressure sensitive indication. These arrangements are shown in Figure 2.

In principle, an aft location for the flow measurement apparatus is highly undesirable. Neither the flow pattern nor the temperature of the air in the motor housing plenum (entrance to the exit orifice) are well known or necessarily stable. The exhaust orifice (multihole or single hole) and associated pressure transducer (mechanical or rotameter), therefore, must be calibrated even more carefully than would ordinarily be expected. To accomplish this, an orifice meter functioning as a secondary standard is mounted ahead of the motor and blower assembly. Schematics of two such arrangements are shown in Figure 3. In the one case the entire filter assembly is removed and replaced with an orifice flow meter which has been calibrated previously against a primary standard. In the second case, a multihole orifice plate and manometer, previously calibrated against a similar primary standard, fits directly onto the filter holder. This latter arrangement was developed to avoid changing the physical configuration of the sampler during calibration. In both cases, however, the secondary standard flow meter is essentially an orifice that has been calibrated against a primary standard (Roots meter).

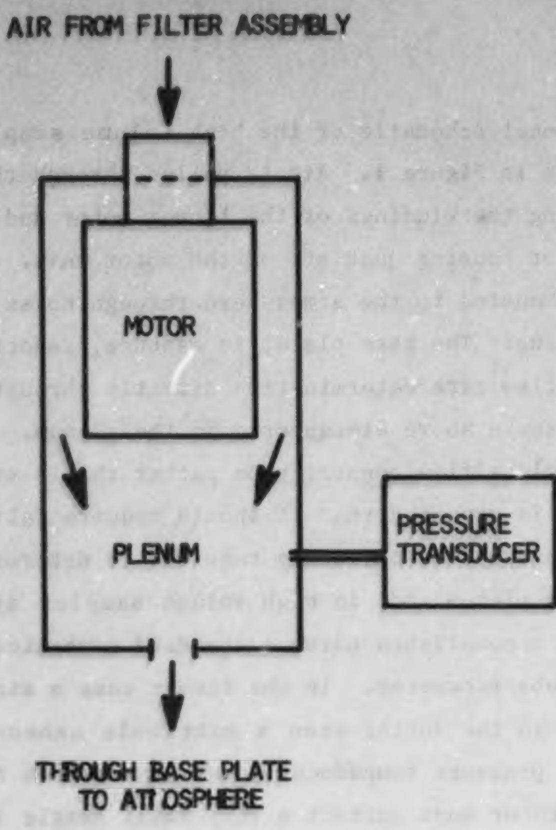

AIR FROM FILTER ASSEMBLY
MOTOR
PLENUM
PRESSURE TRANSDUCER
THROUGH BASE PLATE TO ATMOSPHERE

Figure 1. Primary flow through high volume sampler.

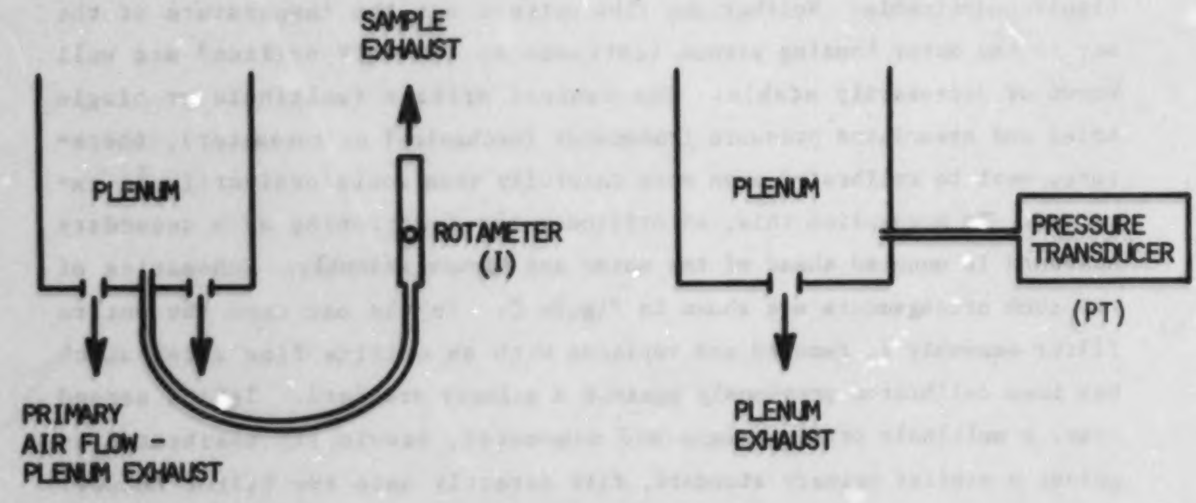
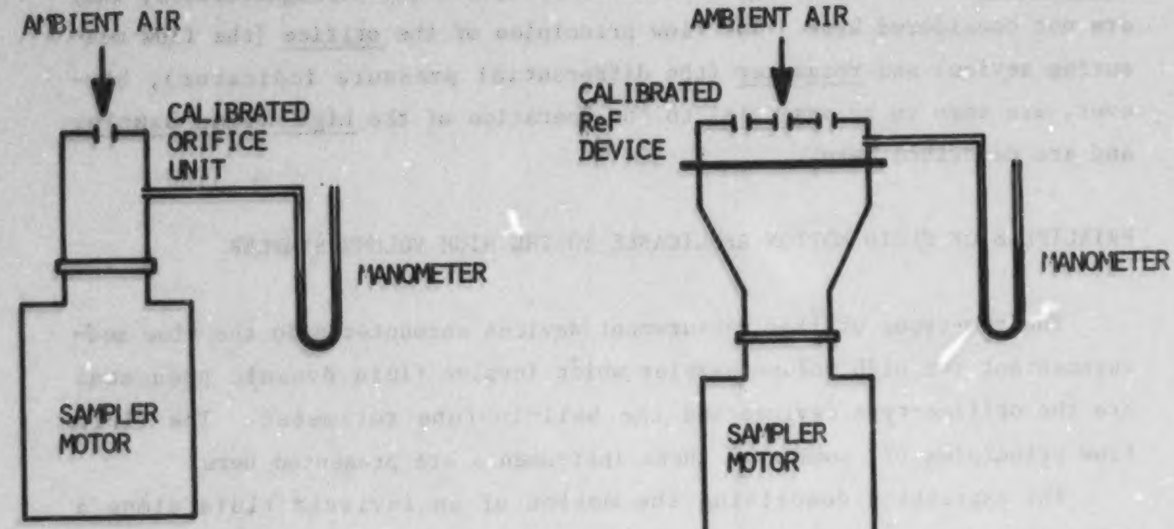

SAMPLE EXHAUST
PLENUM
ROTAMETER (I)
PRIMARY AIR FLOW - PLENUM EXHAUST
PLENUM
PRESSURE TRANSDUCER
(PT)
PLENUM EXHAUST

Figure 2. Gage pressure sensors used in the high volume sampler exhaust.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CALIBRATED
ORIFICE
UNIT
MANOMETER
SAMPLER
MOTOR
AMBIENT AIR
CALIBRATED
ReF
DEVICE
MANOMETER
SAMPLER
MOTOR

Figure 3. Secondary standards for flow calibrations.

In the high volume sampler, the primary flow measurement is seen to be made using orifice-type devices in both field situations and calibration procedures. Various pressure sensors, however, are used to indicate the pressure drop across the constrictions, and one, the ball-in-tube rotameter, actually draws some small flow in providing its pressure indication. The rotameter is not normally used in this indirect manner and is, in itself, a reliable flow indicator when properly sized. Its principle of operation is different from that of an orifice meter, although still based on fluid dynamic phenomena. Since the operation of manometers and mechanical pressure transducers as pressure drop indicators is relatively straightforward, they are not considered here. The flow principles of the orifice (the flow measuring device) and rotameter (the differential pressure indicator), however, are seen to be essential to the operation of the high volume sampler and are described here.

PRINCIPLES OF FLUID MOTION APPLICABLE TO THE HIGH VOLUME SAMPLER

The two types of flow measurement devices encountered in the flow measurementsof the high volume sampler which involve fluid dynamic phenomena are the orifice-type devices and the ball-in-tube rotameter. The fluid flow principles (7) common to these instruments are presented here.

The expression describing the motion of an inviscid fluid along a streamline is generally obtained by omitting the viscous terms in the Navier-Stokes equations of fluid motion and is

$$d\ (V^2/2) + dP/\rho = 0 \quad , \qquad (7)$$

where V is the velocity, P the pressure, and ρ the density of the fluid. The first term represents the differential change in kinetic energy along the flow path, while the second term represents the differential change in enthalpy along the flow path. For liquids, ρ is normally assumed to be a constant, where for a gas such as air under inviscid and thermodynamically reversible flow conditions, the expression $\rho = C \times P^{1/k}$ applies where k is the specific heat ratio of the gas. If the flow field of the gas is such that at every point along the flow path the local velocity is considerably below the sonic velocity at that point, i.e., V/c is less than 1, then the actual change in density will not be significant and it is proper to assume ρ = constant even though the substance is a gas. Thus, we have the concept of the incompressible (ρ = constant), low speed, flow of a gas, which is the situation most commonly of pertinence to the high volume sampler.

Equation (7), written for an incompressible substance becomes

$$d\,(V^2/2 + P/\rho) = 0 \tag{8}$$

$$V^2/2 + P/\rho = \text{constant} \tag{9}$$

or

$$V_1^2/2 + P_1/\rho = V_2^2/2 + P_2/\rho = \text{constant} \tag{10}$$

which is known as Bernoulli's equation. Subscripts 1 and 2 refer to two arbitrary locations which might be of interest along the flow path. It should also be noted that elevation changes along the flow path have been omitted since these are not of significance in the traverse of air from the inlet to the exit of a high volume sampler. Thus, the P refers directly to the static pressure.

If a stream tube is visualized as encompassing the streamline referred to above and if the velocity and pressure are assumed not to vary over the cross section of the stream tube, then the volume flow rate through the tube is given by

$$Q = V_1 A_1 = V_2 A_2 \tag{11}$$

and Equation (10) becomes

$$P_1 - P_2 = (\rho Q^2/2A_2^2)\,[1 - (A_2/A_1)^2] \tag{12}$$

for an inviscid stream tube. Here P_1 and P_2 refer to the assumed uniform pressures over the flow areas A_1 and A_2, respectively. Thus, if the flow through a flow passage could be considered inviscid, then Q could be determined from Equation (12) by measuring P_1 and P_2 at A_1 and A_2, and using the

the expression

$$Q = (\sqrt{2}\ A_2/[1 - (A_2/A_1)^2]^{1/2})\ [(P_1 - P_2)/\rho]^{1/2} \quad . \qquad (13)$$

Orifice - Flow Measuring Devices

For the case of a sharp edged orifice, in which P_1 is measured upstream (near A_1) and P_2 is measured downstream (near the vena contracta of the issuing jet), $A_2 = C_{ci}A_o$, where A_o is the actual orifice area, and C_{ci} is the ideal jet contraction coefficient defined as $C_{ci} = A_2$ (minimum)/A_o. Thus, for an ideal orifice

$$Q = ((C_{ci}\sqrt{2}\ A_o)/[1 - C_{ci}^2(A_o/A_1)^2]^{1/2})[(P_1 - P_2)/\rho]^{1/2} \qquad (14)$$

where it is assumed that P_2 is measured at the minimum flow area.

For the case of an ideal orifice in a very large reservoir, A_o/A_1 approaches 0, thus

$$Q = \sqrt{2}\ C_{ci}\ A_o\ [(P_1 - P_2)/\rho]^{1/2} \quad . \qquad (15)$$

The contraction coefficient for an ideal jet can be predicted, although it is a complicated determination and basically occurs because the streamlines entering the orifice have curvature and must be physically continuous. Thus, the flow area continues to decrease beyond the orifice for a distance of several orifice diameters, whereupon it remains of uniform area. In gas flows, the vena contracta can be predicted using "gas dynamics" principles.

In any real system involving the flow of a real fluid, viscosity and frictional effects will certainly be present. To take these into account, efficiencies are usually defined. In the case of a nozzle it is customary to define the nozzle efficiency as $(V^2/2)$ actual/$(V^2/2)$ ideal. In the case of a jet (or orifice) it is customary to define a "velocity coefficient" as $C_v = V_{actual}/V_{ideal}$. Physically, the effect of viscosity is to (a) reduce the velocity in the issuing jet, (b) alter the contraction coefficient slightly from C_{ci} to C_c, and (c) force the issuing jet to diverge after the vena contracta rather than remain a parallel flow. All of these are accounted for by defining the C_v. Thus, for an actual orifice, equations (14) and (15) become

$$Q = ([\sqrt{2}\ (C_v \times C_c)\ A_o]/[1 - C_c^2\ (A_o/A_1)^2]^{1/2})\ [(P_1 - P_2)/\rho]^{1/2} \quad (16)$$

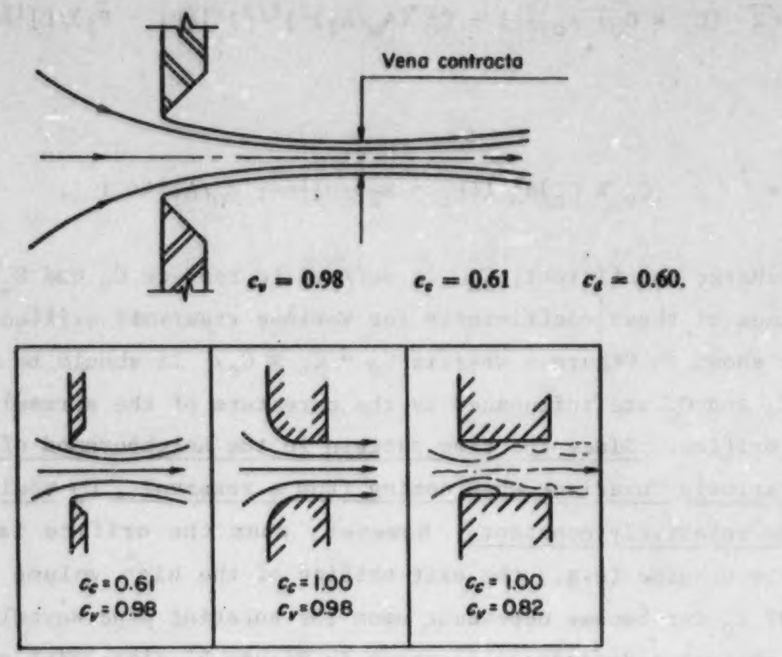
and

$$Q = \sqrt{2}\ (C_v \times C_c) A_o\ [(P_1 - P_2)/\rho]^{1/2};\ A_o/A_1 \ll 1\ . \quad (17)$$

Often a discharge coefficient, C_d, is defined to replace C_v and C_c. Some typical values of these coefficients for various reservoir orifice configurations are shown in Figure 4 wherein $C_d = C_v \times C_c$. It should be noted that both C_v and C_c are influenced by the curvature of the streamlines entering the orifice. Since the flow pattern in the neighborhood of the orifice is relatively invariant when coming from a reservoir, C_d would be expected to be relatively constant. However, when the orifice is mounted within a tube or pipe (e.g., the exit orifice of the high volume sampler) the value of C_d can become dependent upon the entering pipe Reynolds number. An example of such a dependency is shown in Figure 5, along with a schematic of a standard pipe orifice with flange taps. In this case, the discharge coefficient is defined as before, but the contraction coefficient C_c can be asumed to be unity since the pressure taps for P_1 and P_2 are immediately adjacent to the orifice rather than upstream and downstream. For certain combinations of A_o/A_1 the pipe Reynolds number, C_d is seen to be a constant, a characteristic which is essential for an orifice to function properly as a flow meter. If the ratio of A_o^2/A_1^2 is very small, say 0.3, it can be seen that C_d is essentially a constant over all Reynolds numbers.

Up to this point, the discussion on orifices has been general. For the remainder of this section, the discussion will be focused on the application of orifices as flow measurement devices on the high volume sampler. There are three measures of flow rate that are commonly used in high volume sampling. The three measurements and their relationships to each other are discussed below.

The orifice equation, Equation (17), for the orifice calibration unit using a water manometer as the differential pressure indicator can be written as:


Vena contracta
$c_v = 0.98$
$c_c = 0.61$
$c_d = 0.60.$
$c_c = 0.61$
$c_v = 0.98$
$c_c = 1.00$
$c_v = 0.98$
$c_c = 1.00$
$c_v = 0.82$

(C_v = velocity coefficient, C_c = contraction coefficient, and C_d = discharge coefficient).

Figure 4. Flow through various types of orifices. Typical values of the velocity and contraction coefficients are noted for each type.

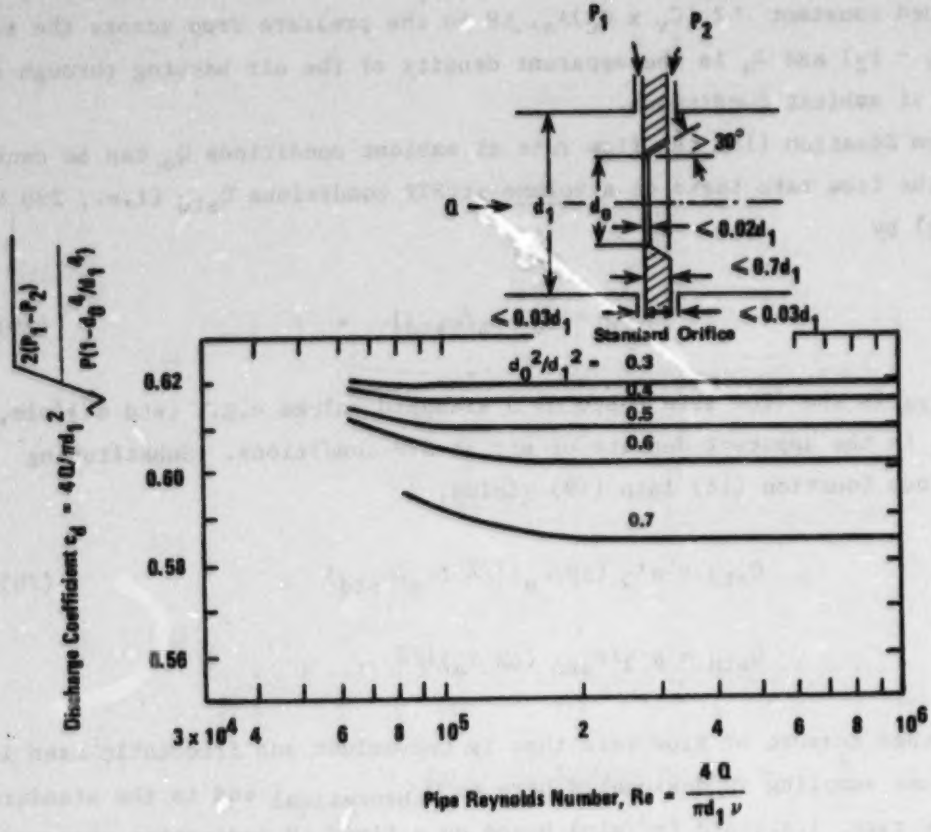


Figure 5. Discharge coefficient as a function of Reynolds number for various ratios of $(d_o/d_1)^2$ for the type of orifice shown. The Reynolds number is based on the average velocity in the pipe and the pipe diameter. (Based on the data from Report T.M. 952, Nat. Aero. and Space Adm., formerly NACA).

$A_o = \frac{\pi d_o^2}{4}$ and $A_1 = \frac{\pi d_1^2}{4}$

$$Q_a = a'_3 (\Delta H/\rho_a)^{1/2} \tag{18}$$

where Q_a is the flow rate through the orifice at ambient conditions, a'_3 is a combined constant $\sqrt{2}\,(C_v \times C_c)A_o$, ΔH is the pressure drop across the orifice $(P_1 - P_2)$ and ρ_a is the apparent density of the air passing through the orifice at ambient conditions.

From Equation (18) the flow rate at ambient conditions Q_a can be converted to the flow rate based on a volume at STP conditions Q_{std} (i.e., 298 K and 760 mmHg) by

$$Q_{std} = Q_a (\rho_a/\rho_{std}) \tag{19}$$

where Q_{std} is the flow rate based on a standard volume e.g., (std m^3)/min, and ρ_{std} is the apparent density of air at STP conditions. Substituting for Q_a from Equation (18) into (19) yields,

$$Q_{std} = a'_3 (\Delta H/\rho_a)^{1/2} (\rho_a/\rho_{std}) \quad , \tag{20}$$

$$Q_{std} = a'_3/\rho_{std} (\Delta H\ \rho_a)^{1/2} \quad .$$

Another measure of flow rate that is convenient and frequently used in high volume sampling is designated here as $Q_{theoretical}$ and is the standardized flow rate, i.e., std (m^3/min) based on a fixed ΔH indication observed at ambient conditions. It is given by the relationship

$$Q_{theoretical} = a'_3 (\Delta H/\rho_{std})^{1/2} \quad . \tag{21}$$

To simplify implementation of the above equations the density is treated as a function of pressure and temperature, two easily measured quantities, in the following manner. From the perfect-gas law

$$PV = nRT = (m/mw)RT \quad , \tag{22}$$

and substituting $\rho = m/V$ into the above relationship yields

$$\rho = (mw/R)\ P/T \quad , \tag{23}$$

where n is the total number of moles of the different gases in the volume V of air at P and T, m is the mass of the n moles of the gases, mw is the apparent molecular weight of the air, and R is the gas constant in appropriate units.

For STP conditions the molecular weight mw of air varies by less than one percent in going from dry to 100 percent relative humidity conditions. Thus, at STP conditions Equation (23) becomes

$$\rho_{std} = (mw/R)\ P_{std}/T_{std} = \text{constant} \quad . \qquad (24)$$

Furthermore, for the pressure and temperature combinations likely to be encountered in high volume sampling the molecular weight of air, if assumed to be constant, would not introduce a significant error into the flow rate determinations. For example, the molecular weight of air varies by 3.5 percent in going from dry to 100 percent relative humidity at 600 mmHg and 40°C (104°F). The change is even less at higher pressures and/or lower temperatures. Also, since flow rate is a function of the square root of density and thus of molecular weight, the resulting error in flow rate would be 1.75 percent for the above conditions. It is seen then that treating the molecular weight of air as a constant would introduce a 2 percent error in the flow rate measurement only under relatively extreme combinations of pressure and temperature. Under this assumption, i.e., mw = constant, Equation (23) becomes

$$\rho_a = R'\ P_b/T_a \quad , \qquad (25)$$

where R' = mw/R = constant.

Based on the two assumptions made in Equations (24) and (25) the three measures of flow rate given by Equations (18), (20) and (21) are:

$$Q_a = a_3\ (\Delta H\ T_a/P_b)^{1/2} \qquad (26)$$

$$Q_{std} = a_2\ (\Delta H\ P_b/T_a)^{1/2} \quad \text{, and} \qquad (27)$$

$$Q_{theoretical} = a_1\ (\Delta H)^{1/2} \quad . \qquad (28)$$

The combined constants a_3, a_2, and a_1 are $a'_3 (R/mw)^{1/2}$, $a'_3/\rho_{std} (mw/R)^{1/2}$, and $a'_3/(\rho_{std})^{1/2}$, respectively.

The relationship between Q_{std} and Q_a is seen from Equation (19) to be

$$Q_{std} = Q_a (P_b/T_a)(T_{std}/P_{std}) \quad . \qquad (29)$$

Also, Equations (18) and (21) show that for a fixed ΔH indication $Q_{theoretical}$ and Q_a are related as

$$Q_{theoretical} = Q_a [(P_b/T_a)(T_{std}/P_{std})]^{1/2} \quad . \qquad (30)$$

Differential Pressure Measurement Device (Ball-in-Tube Rotameter)

The high volume samplers in this study were equipped with either a mechnical pressure transducer or a rotameter to measure the pressure drop across the exhaust orifice in the same manner that a water manometer is used to measure the pressure drop across the orifice calibration unit. The assumption made in using the rotameter as a differential pressure indicator is that the rotameter, like the water manometer and mechanical pressure transducer, is relatively insensitive to ambient pressure and temperature conditions over the range encountered in high volume sampling. The experimental program discussed in Section 4 evaluated this assumption. The ball-in-tube rotameter is a device which operates in a manner somewhat analogous to that of an orifice, although with one distinctly different characteristic: it is, instead, a variable area and approximately constant pressure drop orifice-type device. The orifice area is the ring annulus between the float and the tapered tube and becomes larger as the flow rate increases. Thus, the orifice equation for this application can be written in the form

$$Q_R = ([C_{dr} A_o(I^2)]/[1 - (A_o/A_1)^2]^{1/2})[2(P_1 - P_2)/\rho]^{1/2} \quad , \qquad (31)$$

where Q_R is the flow rate through the rotameter, C_{dr} is the rotameter discharge coefficient, and the contraction coefficient C_c has been assumed to be approximately 1 since the constriction would be rounded at the orifice area. The orifice area $A_o(I^2)$ would be $\pi (D^2 - d^2)/4$, where D is the tube diameter and d the float diameter. Thus, $A_o(I^2) = A_o(D^2)$, since for a tapered tube with a linear scale, I is proportional to D. The area ratio A_o/A_1 can be expressed as approximately equal to $(D^2 - d^2)/D^2$. The pressure drop, $P_1 - P_2$, is that which is necessary to overcome the weight of the float in the flowing fluid and should be approximately constant. Thus, for a given rotameter and float, the flow rate should be proportional to some function of D^2, $f(D^2)$, and thus through calibration Q_R is related to D^2 (or some indicator reading). If the reading I is linearly related to D, then Q_R is related to I^2. If I is linearly related to D^2, then Q_R is related to I, and D is proportional to $I^{1/2}$. The actual form of the relationship between Q_R and I (or D) can be seen to be

$$Q_R = (\text{constant}) \times A_o/[1 - (A_o/A_1)^2]^{1/2} , \qquad (32)$$

which is a rather complicated function of I (or D). Thus, it is expected that a simple linear-regression-type calibration of Q_R versus I would be accurate for a rotameter only over a limited range of Q_R, and that perhaps a better fit could be obtained with a power-law-type of expression such as Q_R versus I^n. Clearly, the appropriate form of this expression depends ultimately upon the character of the rotameter in use: its range of operation, the manner in which the calibration expression is to be utilized and the desired accuracy. Thus, unlike the orifice, the rotameter is not immediately calibrated as a Q_R versus the square root of indication (I) although it may turn out that in the desired range of flow this type of relationship is satisfactory.

It is difficult to proceed beyond Equation (31) in explicitly formulating the flow equations for a rotameter with the ball-in-tube configuration. Clearly, each different location of the ball provides a different flow area and flow pattern in the annulus. Also, it can be seen that there is a viscous drag in addition to the pressure differential which supports the weight of the ball. Clearly, this effect is one that will introduce a flow rate as well as a viscosity influence, and certainly a temperature influence via the viscosity. At low flow rates and low pipe Reynolds number, the added effect of the Reynolds number on C_{dr} will become significant. Both of these phenomena have been studied (8,9) and both serve to additionally confuse the Q_R versus I relationship which should define the proper type of calibration formulation. The usual practice is to calibrate the rotameter directly with the fluid to be observed and at the operating temperature, so that the viscosity ν does not change. Whenever these conditions are not met, the validity of the calibration becomes suspect. In fact, it was shown (9) that the calibration must involve the quantities and functional relation

$$Q_R \times D/(D^2 - d^2)\nu = F[D/d,\ d^3\ (\rho-\sigma)/\nu^2\sigma] \quad , \qquad (33)$$

where F is the correlation function, D and d the tube and ball diameters, respectively, ρ and σ the fluid and float densities, respectively, and ν the dynamic viscosity, which is moderately temperature dependent. Thus, assessing the variations of ν and ρ on the calibration of a rotameter without knowing F completely, is seen to be a very difficult task.

CALIBRATION OF THE SECONDARY STANDARDS

The two secondary standards used, (a) the orifice calibration unit and (b) the reference flow (ReF) device, are both basically orifice-type instruments and should be calibrated similarly. A proper calibration of the secondary standard can be achieved using any one of the three measures of flow rate given by Equations (26), (27), and (28). If the primary standard is a Roots meter with the arrangement shown in Figure 6, then the flow rate through the Roots meter Q_m at meter conditions is

$$Q_m = V_m(m^3)/t(min),\ m^3/min \qquad (34)$$

where V_m is the volume measured by the Roots meter over a time period, t, assuming a constant flow. The flow rate through the orifice at ambient conditions is

$$Q_a = [V_m(m^3)/t(min)]\ (P_m/P_b)(T_a/T_m) \quad , \text{ or} \qquad (35)$$

$$Q_a = [V_m(m^3)/t(min)](P_m/P_b), \text{ assuming } T_a \simeq T_m \quad , \text{ and} \qquad (36)$$

$$Q_a = [V_m(m^3)/t(min)][(P_b - \Delta P)/P_b] \quad , \qquad (37)$$

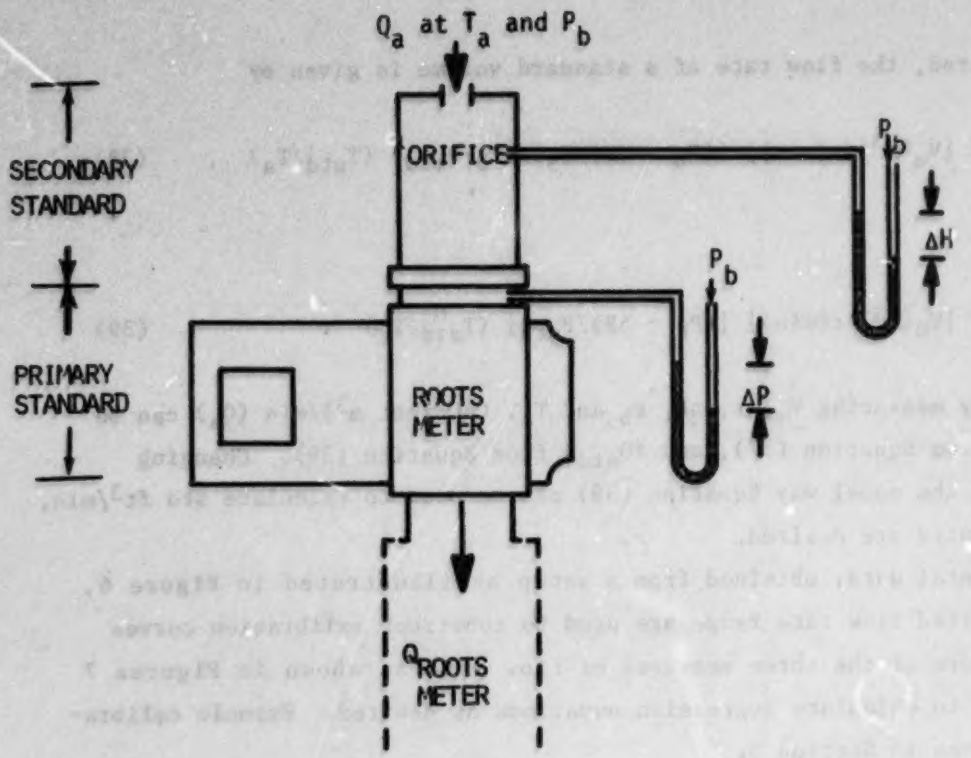

Q_a at T_a and P_b
SECONDARY STANDARD
ORIFICE
P_b
ΔH
P_b
ΔP
PRIMARY STANDARD
ROOTS METER
$Q_{\text{ROOTS METER}}$

Figure 6. Primary Calibration of Secondary Standards with a Roots Meter.

where $P_m = P_b - \Delta P$, ΔP is the differential pressure drop from ambient to the inlet of the Roots meter.

If desired, the flow rate of a standard volume is given by

$$Q_{std} = [V_m(m^3)/t(min)]\ [(P_b - \Delta P)/P_b]\ (P_b/P_{std})\ (T_{std}/T_a) \quad , \qquad (38)$$

or

$$Q_{std} = [V_m(m^3)/t(min)]\ [(P_b - \Delta P)/P_{std}]\ (T_{std}/T_a) \quad . \qquad (39)$$

Then, by measuring V_m, t, ΔP, P_b and T_a, (ambient m^3)/min (Q_a) can be calculated from Equation (37), and (Q_{std}) from Equation (39). Changing the units in the usual way Equation (39) can be used to calculate std ft^3/min, if English units are desired.

Experimental data, obtained from a setup as illustrated in Figure 6, over the desired flow rate range are used to construct calibration curves for one or more of the three measures of flow rate as shown in Figures 7 through 9 or to calculate regression equations as desired. Example calibrations are given in Section 5.

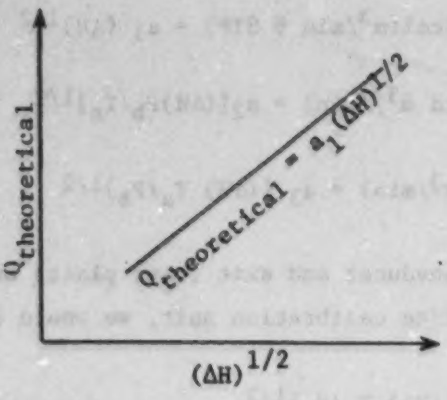
Any plotting other than the above three will require a family of lines when ambient conditions vary, and may produce erroneous results when applied.

CALIBRATION OF THE FLOW INDICATORS

The two indicators used, (a) the pressure transducer and (b) the rotameter, are instruments similar in their applications although somewhat different in their basis of operation. The pressure transducer is a simpler and more forthright device and will be discussed first.

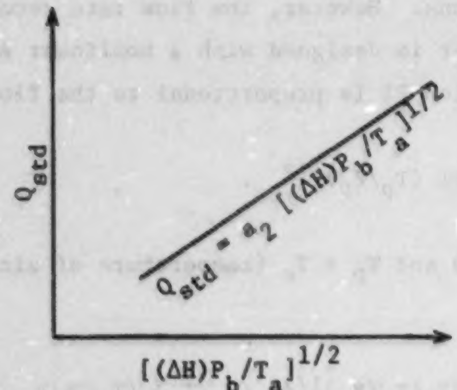
Pressure Transducer

Consider the arrangements in Figure 2 and 3, and assume that the secondary standard has a calibration expression in one of the forms



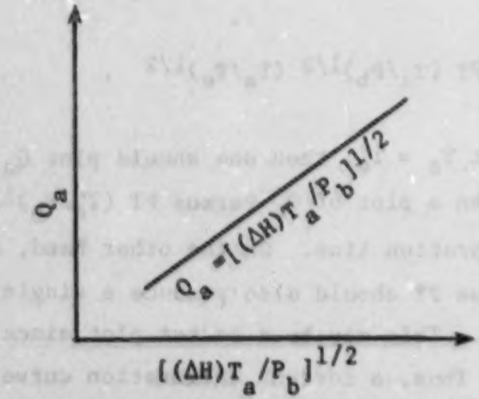
$Q_{\text{theoretical}}$
$Q_{\text{theoretical}} = a_1 (\Delta H)^{1/2}$
$(\Delta H)^{1/2}$

Figure 7. Calibration of secondary standards in terms of a standard (theoretical) flow rate.



Q_{std}
$Q_{\text{std}} = a_2 [(\Delta H) P_b / T_a]^{1/2}$
$[(\Delta H) P_b / T_a]^{1/2}$

Figure 8. Calibration of secondary standards in terms of a "standardized-volume" flow rate.



Q_a
$Q_a = [(\Delta H) T_a / P_b]^{1/2}$
$[(\Delta H) T_a / P_b]^{1/2}$

Figure 9. Calibration of secondary standard in terms of an actual flow rate.

$$Q_{\text{theoretical}(m^3/\text{min @ STP})} = a_1\ (\Delta H)^{1/2} \tag{40}$$

$$Q_{\text{std}}\ [(\text{std } m^3)/\text{min}] = a_2[(\Delta H)P_b/T_a]^{1/2} \tag{41}$$

$$Q_a\ (\text{amb } m^3/\text{min}) = a_3\ [(\Delta H)\ T_a/P_b]^{1/2}\ \ . \tag{42}$$

Now, since the pressure transducer and exit (base plate) orifice operate in the same manner as the orifice calibration unit, we would expect that

$$Q_p = c_4\ [(P')\ T_p/P_p]^{1/2}$$

where Q_p is the flow through the exit orifice at plenum conditions (P') is the pressure excess in the exhaust plenum above ambient, and the subscript P refers to plenum conditions. However, the flow rate recording chart used with the pressure transducer is designed with a nonlinear scale such that the pressure transducer indiction PT is proportional to the flow rate making

$$Q_p = c_4\ PT\ (T_p/P_p)^{1/2}\ \ . \tag{43}$$

Now, $Q_p = Q_a\ (P_b/P_p)(T_p/T_a)$ and $T_p \approx T_e$ (temperature of air in the pressure transducer). Thus,

$$\begin{aligned} Q_a &= c_4\ PT\ (T_e/P_p)^{1/2}\ \ (P_p/T_e)\ (T_a/P_b)\ ,\ \text{or} \\ &= c_4\ PT\ (T_a/P_b)^{1/2}\ [(P_p/T_e)(T_a/P_e)]^{1/2}\ \ . \end{aligned} \tag{44}$$

Since $P_p/P_e \approx 1$,

$$Q_a = c_4\ PT\ (T_a/P_b)^{1/2}\ (T_a/T_e)^{1/2}\ \ . \tag{45}$$

Now, if it is expected that $T_a \approx T_e$, then one should plot Q_a versus PT $(T_a/P_b)^{1/2}$. If not, then a plot of Q_a versus PT $(T_a/P_b)^{1/2}$ $(T_a/T_e)^{1/2}$ should yield a single calibration line. On the other hand, a plot of Q_a $(P_b/T_a)^{1/2}$ $(T_e/T_a)^{1/2}$ versus PT should also produce a single correlation for all ambient conditions. This may be a better plot since Q_a is already known from Equation (42). Thus, a correct calibration curve would appear as shown in Figure 10.

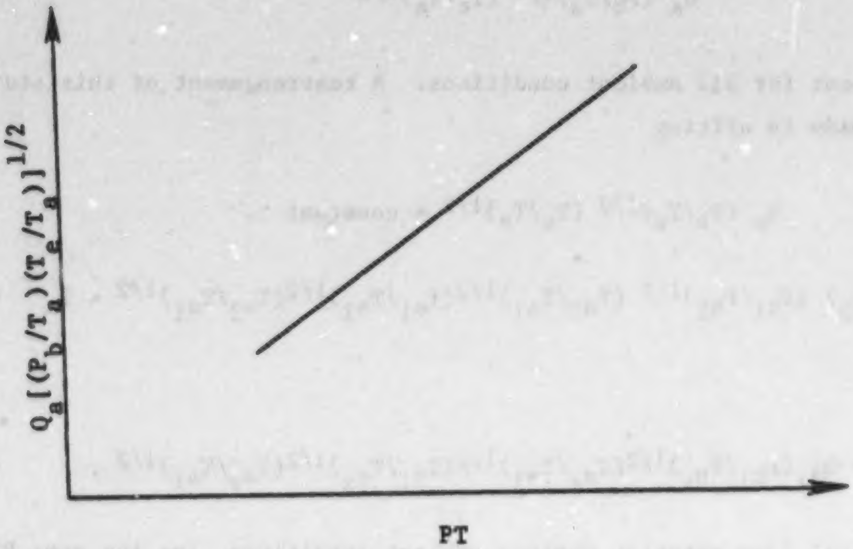


Figure 10. Calibration of the pressure-transducer-type indicator.

This result indicates that for one value of PT the quantity

$$Q_a\ (P_b/T_a)^{1/2}\ (T_e/T_a)^{1/2}$$

will be constant for all ambient conditions. A rearrangement of this statement can be made in writing

$$Q_a\ (P_b/T_a)^{1/2}\ (T_e/T_a)^{1/2} = \text{constant} \quad .$$

Thus, $$(Q_{a_1}/Q_{a_2})\ (P_{b_1}/P_{b_2})^{1/2}\ (T_{a_2}/T_{a_1})^{1/2}(T_{e_1}/T_{e_2})^{1/2}(T_{a_2}/T_{a_1})^{1/2} = 1 \qquad (47)$$

or

$$Q_{a_x} = Q_{a_1}(P_{b_1}/P_{b_x})^{1/2}(T_{a_x}/T_{a_1})^{1/2}(T_{e_1}/T_{e_x})^{1/2}(T_{a_x}/T_{a_1})^{1/2} \ . \qquad (48)$$

Thus, the actual flow rates at various ambient conditions, for the same PT, are related. As an example, the validity of the relationship in Figure 10 is evaluated with experimental data in Section 5.

Rotameter

As indicated above, the rotameter is fundamentally a quite different instrument from the pressure transducer and exit orifice. A rotameter is a constant pressure-drop and variable area device, whereas an orifice is a constant area and variable pressure drop instrument. However, the small rotameter used with the high volume sampler is used only as a sampler, in that only a very small fraction of the actual flow is channeled through the rotameter. Instead, it primarily functions as an indicator of the excess pressure in the motor housing just upstream of the base plate which, in essence, acts as an exit orifice. Thus, in its use with the high volume sampler, the rotameter is analogous to the pressure transducer and, primarily, is an instrument that provides an indication of the pressure drop across the base plate orifice. This is seen in Figure 11.

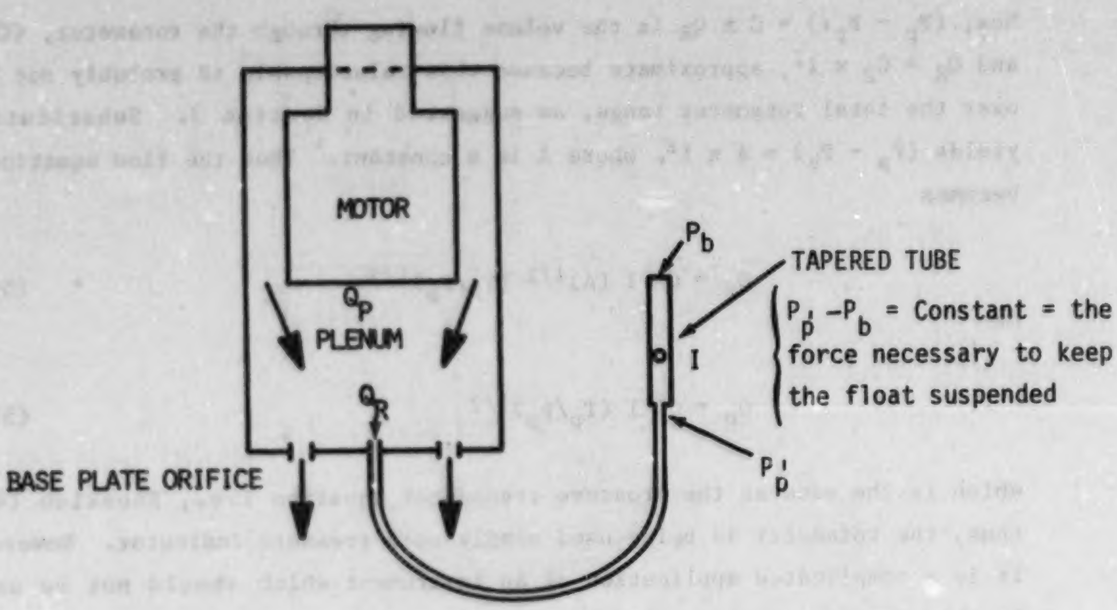

MOTOR
Q_P
PLENUM
Q_R
BASE PLATE ORIFICE
P_b
TAPERED TUBE
$P_p' - P_b$ = Constant = the force necessary to keep the float suspended
I
P_p'

Figure 11. Rotameter Indicator

The orifice equation for the base plate can be written as

$$Q_p = C \ [(P_p - P_b)/\rho_p]^{1/2} \ . \tag{49}$$

Now, $(P_p - P_{p'}) = C \times Q_R$ is the volume flowing through the rotameter, $<<Q_p$, and $Q_R \approx C_2 \times I^2$, approximate because this relationship is probably not true over the total rotameter range, as suggested in Section 3. Substitution yields $(P_p - P_b) = A \times I^2$, where A is a constant. Thus the flow equation becomes

$$Q_p = C' \ I \ (A)^{1/2} \ (T_p/P_p)^{1/2} \tag{50}$$

or

$$Q_p = C'' \ I \ (T_p/P_p)^{1/2} \tag{51}$$

which is the same as the pressure transducer equation i.e., Equation (43) thus, the rotameter is being used simply as a pressure indicator. However, it is a complicated application of an instrument which should not be used in this manner. Nonlinearity, as well as some very significant temperature effects, often make it unreliable, especially in this manner of application.

Now, assuming that the rotameter is analogous to the pressure transducer, and that I^2 is proportional to the pressure drop across the base plate, all of the data taken with this instrument can be correlated as done with Equation (45) and the example which followed. Simply replace PT with I. In looking at the data in the study, it is apparant that T_e should be included if available because of its apparant stronger influence on the rotameter than on the pressure transducer, an expected result.

CONVERSION EQUATIONS

The expressions of flow rate -- $Q_{theoretical}$, Q_a, and Q_{std} -- can be readily converted from one to the other if the ambient conditions are known. The conversion equations for the three expresions of flow rate are

$$Q_{std} = Q_a\ (P_b/P_{std})\ (T_{std}/T_a) = 0.392\ Q_a\ (P_b/T_a)\ ; \tag{52}$$

$$\begin{aligned} Q_{theoretical} &= Q_a\ (P_b/P_{std})^{1/2}\ (T_{std}/T_a)^{1/2} \\ &= 0.626\ Q_a\ (P_b/T_a)^{1/2}\ ;\ \text{and} \end{aligned} \tag{53}$$

$$\begin{aligned} Q_{std} &= Q_{theoretical}\ (P_b/P_{std})^{1/2}\ (T_{std}/T_a)^{1/2} \\ &= 0.626\ Q_{theoretical}\ (P_b/T_a)^{1/2}\ . \end{aligned} \tag{54}$$

It is important to note under sampling conditions such that $T_a = T_{std} = 298$ K and $P_b = P_{std} = 760$ mmHg, then $Q_a = Q_{std} = Q_{theoretical}$. A mistake made quite frequently is to report $Q_{theoretical}$ (m^3/min at STP) as Q_{std} (std m^3)/min.

SECTION 4
EXPERIMENTAL PROCEDURES AND RESULTS

GENERAL

The primary objective of this experimental program was to evaluate the accuracy with which the temperature and pressure correction techniques as incorporated into the calibration equations derived in Section 3 predict the temperature and pressure effects on flow rate. Tests were conducted over temperature and pressure ranges normally encountered in field sampling.

Secondary objectives were to compare two secondary calibration devices, namely the orifice calibration unit as described in the EPA Reference Method, and the ReF device used in the QAB/EMSL audit program, then to compare two primary calibrations conducted at significantly different barometric pressures using different primary standards.

EVALUATION OF PRESSURE AND TEMPERATURE CORRECTION PROCEDURES

Background

Prior to designing the experimental program studies were made of the Federal Register Method (1), the present use of different measures of flow rate for field programs and the feasibility of treating the molecular weight of air as a constant. These special studies are discussed in the order listed. A review of the procedures for calibration of flow rate indicators follows the above discussions.

Procedures in Federal Register Method -- Flow rate calibration procedures given in the Federal Register method are: to establish the relationship of the actual flow rate at ambient conditions to the pressure drop across the orifice calibration unit over the flow rate range of interest, and to calibrate the high volume sampler using the above orifice calibration to

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establish the relationship between the flow rate corrected to ambient conditions (if the ambient conditions at the time of sample calibration differ significantly from the conditions existing when the orifice was calibrated) and the sampler's flow rate indicator readings.

During sampler operation the flow rate is determined using the flow rate indication and the sampler's calibration curve or equation. The resultant flow rate is a theoretical (or reference) flow rate standardized to the temperature and pressure conditions at the time of the sampler calibration, or to the conditions existing at the time of the orifice calibration if no temperature or pressure corrections were made at the time that the sampler was calibrated.

There is nothing technically wrong with the above procedure. However, this procedure does not provide a basis for comparing TSP data across programs, agencies, etc. unless temperature and pressure conditions on which the sampler calibration was based plus the conditions existing in the field when the actual measurement was made are known.

Misconceptions of Measures of Flow Rate — There appears to be some confusion concerning the different measures of flow rate by individuals using the high volume method. The most common occurance is to confuse a standardized flow rate with a flow based on a standard volume. Being consistent with the notation and definitions in this document, the error is one of calibrating $Q_{theoretical}$ versus I but reporting the measured flow rate as Q_{std}. In cases where $Q_{theoretical}$ has been established for STP conditions the two measures are related by

$$Q_{std} = 0.626 \ Q_{theoretical} \ (P_b/T_a)^{1/2}$$

for ambient conditions of P_b and T_a.

Also there appears to be some confusion concerning the relationship between temperature, pressure and the flow rate based on a standard volume. For example, during calibration Q_{std} is correctly calculated but plotted versus or regressed incorrectly on I $(T/P)^{1/2}$ rather than on I $(P/T)^{1/2}$ as it should be. If calibration was performed at or near STP conditions this error would essentially result in reporting flow rate at ambient conditions

Q_a as the flow based on a standard volume Q_{std}. The relationship between the two measures of flow rate is

$$Q_{std} = Q_a \, (T_{std}/P_{std})(P_b/T_a) \quad .$$

The magnitude of the error resulting from this procedure increases as the difference between standard and field conditions increases.

Treating Molecular Weight of Air as a Constant -- Because barometric pressure and ambient temperature are easily measured or estimated it is desirable to treat the density of air as a function of temperature and pressure. This is feasible if the molecular weight of air and thus the density of air does not vary appreciable with relative humidity for fixed temperature and pressure conditions. The density of air as a function of barometric pressure, temperature, relative humidity and vapor pressure of water is given by (10)

$$\rho_{air} = \frac{0.001293}{1+0.00367t} \quad \frac{P - 0.0038 \, H \, P^t_{H_2O}}{760} \quad .$$

where

ρ_{air} = density of air, g/cm^3
P = barometric pressure, mmHg
H = relative humidity, percent
$P^t_{H_2O}$ = vapor pressure of water, mmHg at t°C
t = ambient temperature, °C.

Using the above relationship the density of air is calculated for dry air (i.e., H = 0) and for a saturated condition (i.e., H = 100) at 25°C and 40°C (104°F) and for pressures of 760 and 600 mmHg as representative of calibration conditions and the somewhat extreme conditions to be encountered in the field, respectively. The calculations are shown in the following table.

P (mmHg)	t (°C)	H (%)	$P^t_{H_2O}$ (mmHg)	ρ_{air} (g/cm^3)
760	25	0	0	0.00118
760	25	100	23.8	0.00117
760	40	0	0	0.00113
760	40	100	55.3	0.00110
600	40	0	0	0.00089
600	40	100	55.3	0.00086

As seen from the above table, the maximum error possible in assuming the density of dry air at 25°C and 760 mmHg is 0.8 percent. At 40°C and 760 mmHg, the maximum error would be 2.7 percent, while at 40°C and 600 mmHg, the error would be 3.4 percent. Furthermore, the calibration equation given in the report is of the form $Q_{std} = a_2\ (\Delta H\ \rho_{air})^{1/2}$, with the flow rate being a function of the square root of the density. Thus, the error in ρ_{air} is reduced by one-half in Q_{std} and would be 0.4, 1.4, and 1.7 percent, respectively, for the above three examples.

From the above analysis, it appears reasonable to assume that flow rate error due to ignoring relative humidity (or changes in the molecular weight) would in nearly all situations be 2 percent or less. Also, it is recognized that most calibrations will be made under conditions different from the extremes of 0 and 100 percent relative humidity. Typically, calibrations and measurements are made at relative humidities between 30 and 70 percent reducing the potential error in the measured flow rate to the order of 1 percent or less.

Review of Flow Indicator Calibration Procedures -- The discussion "Calibration of the Flow Indicators" in Section 3 is summarized here to indicate the points in the calibration and measurement process that are evaluated in this program.

For a high volume sampler such as that illustrated in Figure 11, it can be seen that the rotameter measures pressure above ambient in the plenum for the exhaust orifice. Thus, calibration of the flow through the exhaust orifice and the rotameter would be appropriate using a relationship of the form

$$Q_p = c_4 \, I \, (T_p/P_p)^{1/2} + d_4 \tag{55}$$

where

Q_p = actual flow rate through the exhaust orifice at plenum conditions of T_p and P_p
I = rotameter indication (or pressure transducer indication PT)
T_p = temperature of the sample air in the plenum
P_p = pressure of air in the plenum
c_4 = slope of a linear regression of Q_p on $I \, (T_p/P_p)^{1/2}$
d_4 = intercept of a linear regression of Q_p on $I \, (T_p/P_p)^{1/2}$.

However, the calibration process does not include a means of directly measuring Q_p. But the actual flowrate Q_a through the orifice calibration unit at ambient conditions of T_a and P_b, see Equation (31), is a value easily calculated from the orifice calibration unit regression equation and is related to Q_p by the relationship

$$Q_a = Q_p \, (T_a/T_p) \, (P_p/P_b) \quad .$$

Since the pressure drop is usually on the order of 5 to 10 mmHg (for the sampler with a multi-hole exhaust) we can assume that $P_p/P_b \approx 1$, then the relationship becomes

$$Q_a = Q_p \, (T_a/T_p) \quad . \tag{56}$$

Substituting Q_p from Equation (55) into Equation (56) gives

$$Q_a = c_4 \, I \, (T_a/T_p) \, (T_p/P_p)^{1/2} + d_4 \, (T_a/T_p) \quad . \tag{57}$$

To use Equation (57), values of Q_a are determined from the orifice calibration unit, values of I read from the rotameter for corresponding values of

T_a, T_p, and Q_a, values of P_p are measured by appropriate apparatus during the calibration, and c_4 and d_4 are obtained from regression analysis.

It is obvious that a relationship such as Equation (57) would be difficult to work with. The general assumption made at this point is that the rotameter (or pressure transducer) indication is related to ΔH in some fixed manner and that the relationship is not sensitive to temperature and pressure differences normally encountered in field sampling. It is assumed at this time that ΔH and I are related by

$$\Delta H = a_4\ I^2 + b_4 \quad . \tag{58}$$

Thus, the orifice equation as it applies to the orifice calibration unit,

$$Q_a = a_3\ (\Delta H\ T_a/P_b)^{1/2}$$

where Q_a is the actual flow through the orifice at ambient temperature T_a, barometric pressure P_b and for a specific pressure drop ΔH, becomes

$$Q_a = c_3\ I\ (T_a/P_b)^{1/2} + d_3 \quad , \tag{59}$$

when Equation (58) is substituted into the above equation.

> Note: A "zero intercept" model appears to be valid for the orifice calibration unit itself; however, a significant intercept may be observed for some high volume sampler calibrations.

Using the orifice equation (without an intercept) it can be seen that for a fixed ΔH value, say ΔH', the actual flow rate at, say T_1, P_1 conditions, is

$$Q_{a1} = a_3[(\Delta H')T_1/P_1]^{1/2} \tag{60}$$

and the flow rate that would occur for the same ΔH value at say T_2, P_2 conditions would be

$$Q_{a_2} = a_3 \; [(\Delta H')T_2/P_2]^{1/2} \quad . \qquad (61)$$

From the above relationship it can be seen that if values of T_2 and P_2 are specified, then $Q_{a_2} = [(\Delta H')T_2/P_2]^{1/2}$ is a constant and thus Q_{a_2} is a function of ΔH only.

For the remainder of this section and throughout this document the relationship between $Q_{theoretical}$, the flow rate standardized to 25°C and 760 mmHg the actual flow rate at ambient conditions Q_a is given as

$$Q_{theoretical} = Q_a \; (P_b/T_a)^{1/2} \; (T_{std}/P_{std})^{1/2} \quad . \qquad (62)$$

Furthermore, when T_{std} and P_{std} are defined as 298 K (25°C) and 760 mmHg, respectively, and substituted into Equation (62) it can be seen that

$$Q_{theoretical} = 0.626 \; Q_a \; (P_b/T_a)^{1/2} \quad . \qquad (63)$$

Returning to the high volume sampler flow rate calibration relationship as given by Equation (59) and substituting that value for Q_a into Equation (63) yields the relationship

$$Q_{theoretical} = 0.626 \; (P_b/T_a)^{1/2} \; [c_3 \; I \; (T_a/P_b)^{1/2} + d_3] \quad .$$

Simplifying this relationship gives

$$Q_{theoretical} = 0.626 \; c_3 \; I + 0.626 \; d_3 (P_b/T_a)^{1/2} \quad ,$$

or

$$Q_{theoretical} = c'_3 \; I + d'_3 \; (P_b/T_a)^{1/2} \quad . \qquad (64)$$

In most practical applications, as indicated by the data from this study the intercept term will be less than 10 percent of the flow rate.

Furthermore, for a fixed site the variation in the intercept term from extremes of pressure and temperature will be less than 1 percent of the flow rate.

Therefore, it is further hypothesized here that the high volume sampler flow rate can be adequately predicted from rotameter indications by a relationship of the form

$$Q_{theoretical} = c_1 I + d_1 \quad . \tag{1}$$

It was indeed the objective of this experimental program to test the validity of the above relationship over a wide range of temperature and pressure combinations. The validity of Equation 1 is evaluated experimentally in the following manner.

An orifice calibration unit, having well-known temperature and pressure characteristics, was calibrated in the laboratory with a primary standard yielding a calibration equation of the form

$$Q_a = a_3[(\Delta H)T_a/P_b)]^{1/2} \quad . \tag{65}$$

This orifice calibration unit was then used to calibrate a high volume sampler under different temperature and pressure combinations. For each calibration, values of T_a, P_b and ΔH were determined and used in equation 65 to calculate Q_a. The calculated actual flowrate Q_a at ambient conditions of T_a and P_b was converted to $Q_{theoretical}$ (i.e., the flow rate that would be observed at standard conditions for the same ΔH value) by

$$Q_{theoretical} = 0.626\ Q_a\ (P_b/T_a)^{1/2} \quad . \tag{63}$$

Note: Up to this point all calculations have been based on the secondary standard (i.e., the orifice calibration unit) and thus should be accurate and precise.

Data pairs of $Q_{theoretical}$ (obtained from the secondary standard) and I (rotameter reading) from each run of a calibration were used to calculate a linear regression of $Q_{theoretical}$ on I using the least squares technique yielding a high volume sampler flow rate regression equation of the form

$$Q_{\text{theoretical}} = c_1 I + d_1 .$$

The slopes (c_1's) and intercepts (d_1's) derived from experimental data are tested by analysis of variance for temperature and pressure effects. Also, experimental data are used to verify the assumption that ΔH and I are related by

$$\Delta H = a_4 I^2 + b_4 . \qquad (66)$$

Test Procedures

Two types of high volume samplers were tested. The first type consisted of a multihole exhaust baseplate and a rotameter to measure flow rates. The second sampler had a single-hole exhaust orifice meter and used a pressure transducer to measure flow rates. Two calibration devices, the orifice calibration unit and the ReF device, were used in the testing program.

The orifice calibration unit is the secondary calibration device described in the Reference Method for the Determination of Suspended Particulate in the Atmosphere (High Volume Method)(1).

The ReF device is an orifice meter on an acrylic PVC box fabricated for direct mounting on the filter holder assembly. The ReF device is commercially available and is presently used by the QAB/EMSL in its auditing program.

The testing program included high volume sampler calibrations at four different atmospheric pressures, ranging from approximately 763 mmHg down to 595 mmHg. At each of the atmospheric pressures, each of the high volume samplers were calibrated at four different ambient temperature levels, approximately 10°, 20°, 30°, and 40°C. Four sets of data, one for each high volume sampler system/calibration device combination, were generated. Each set consisted of readings for 5 resistance plates at 16 different ambient temperature/barometric pressure conditions.

Different but relative constant temperatures were achieved through use of air conditioning and heaters in the RTI environmentally controlled mobile laboratory. Different but constant barometric pressures were obtained by stationing the mobile laboratory at different elevations above sea level. Tests were run at the Research Triangle Park and at three different sites (elevations) on Mount Mitchell in North Carolina.

Results

Results of the experimental efforts directed toward determining the temperature and pressure effects on high volume sampler flow rate calibration and measurement are given in this section. The major discussion is directed toward the orifice calibration unit and rotameter configuration, the EPA reference method. Results of the other configurations tested are tabulated and only summarized in the text.

The experimental data (recorded in Appendices A - D) was first used to evaluate the constants in the relationship

$$\Delta H = a_4 I^n + b_4.$$

The nonlinear curve fitting method used here to estimate n, a_4, and b_4 was a modification of the method given by Bevington in the computer program called CURFIT (11). The program CURFIT minimizes the reduced chi-squared value by first approximating the fitting function with the first-order terms of a Taylor's series expansion containing the parameter increments. The reduced chi-squared value is minimized with respect to the parameter increments by setting the derivatives with respect to the parameter increments equal to zero. The resulting set of simultaneous equations containing the error matrix is solved to give the optimum increments for the next iteration. The optimum values for all of the parameters are obtained from the trial value of n which gives the overall minimum reduced chi-squared value. Results of the 16 sets of calibration data for the orifice calibration unit and rotameter combinations were: $n = 1.794 \pm 0.235$, $a_4 = 3.881 \pm 1.125$, and $b_4 = \pm 0.0529$.

Slopes of the high volume sampler flow rate regression equations resulting from calibrations at the different temperature and pressure combinations are given in Table 1. The analysis of variance results are given in Table 2. Results of the analysis of variance are:

1. At the 0.95 confidence level there is no reason to believe that the regression slope is sensitive to pressure variations.
2. At the 0.95 confidence level there is no reason to believe that the regression slope is sensitive to temperature variations.

Also, the average slope c_1 = 34.51 across all temperature and pressure combinations is nearly identical to the slope of 34.04 obtained at near STP conditions (296 K, 760 mmHg). The relative standard deviation of the slopes about that mean is 6 percent, indicating an acceptable level of precision for the field calibrations.

Tables 3 and 4 treat the intercept in the same manner as the slope was treated in Tables 1 and 2. Results of the analysis of variance show that at the 0.95 confidence level neither pressure nor temperature variations have a significant influence on the regression intercept.

Regression constants resulting from calibration of a high volume sampler, equipped with a rotameter with a ReF device are given in Table 5. Temperature and/or pressure trends are not evident (ANOVA was not performed). As seen at the bottom of Table 5, the average slope was 34.91 with a standard deviation of 3.14 (a relative standard deviation of 9 percent), and the average intercept was -9.29 with a standard deviation of 4.43.

Tables 6 and 7 contain the regression constants resulting from calibration of a sampler equipped with a pressure transducer with an orifice calibration unit and a ReF device, respectively. There are no obvious temperature and pressure trends in the data presented in the two tables. The summary statistics show that the orifice calibration unit and the ReF device yield similar average slopes of 1.01 and 1.02 and intercepts of 0.29 and -1.42, respectively. Both devices exhibited about the same level of precision with standard deviations of the slopes of 0.04 and 0.05 for the orifice calibration unit and the ReF device, respectively.

Table 1. COMPARISON OF REGRESSION EQUATION SLOPES FROM ORIFICE CALIBRATION UNIT AND ROTAMETER CALIBRATIONS

Temperature (K)	Pressure (mmHg) 760	711	633	596	Total
283	35.21	32.93	33.89	36.74	139
296	34.04	22.77	30.45	36.51	134
306	35.84	38.37	35.33	32.72	142
316	34.20	37.04	31.41	34.77*	137
Total	139	141	131	141	552

*Missing data point; value inserted is the average of the row and column average slope, c_1 = 34.51, standard deviation of slope, s_{c_1} = 2.14

Table 2. ANALYSIS OF VARIANCE TABLE (SLOPES)

	SS	df	MS
Pressure (Row) means	8.5	3	2.8
Temperature (Column) means	17.0	3	5.7
Residual	58.5	9	6.5
Total	84.0		

Hypothesis 1. There are no pressure effects on the slope.

Hypothesis 2. There are no temperature effects on the slope.

--Calculated F value for pressure $F = 2.8/6.5 = 0.43$

--Calculated F value for temperature $F = 5.7/6.5 = 0.87$

--Tabulated F value for $F_{.95}(3,9) = 3.86$

For both cases the tabulated F value is larger than the calculated F value; therefore, at the 0.95 confidence level neither of the two hypotheses can be rejected. That is, there is no reason to believe that the slope of the regression equation is sensitive to temperature and/or pressure variations.

Table 3. COMPARISON OF REGRESSION EQUATION INTERCEPTS FOR CALIBRATION OF A ROTAMETER WITH AN ORIFICE CALIBRATION UNIT

Temperature (K)	Pressure (mmHg) 760	711	633	596	Total
283	-6.16	-2.97	-2.08	-6.40	-17.6
296	-5.37	-5.06	+0.04	-6.86	-17.2
306	-9.38	-8.30	-6.32	+2.27	-21.7
316	-7.47	-6.11	+1.58	-3.83	-15.8
Total	-28.4	-22.4	-6.7	-14.8	-72.3

*Missing data point; value inserted is the average of the row and column. average intercept, $d_1 = -4.57$, standard deviation of intercept, $s_{d_1} = 3.56$

Table 4. ANALYSIS OF VARIANCE TABLE (INTERCEPTS)

	SS	df	MS
Pressure (Row) means	4.8	3	1.6
Temperature (Column) means	66.4	3	22.1
Residual	107.9	9	12.0
Total	179.1	15	

--Calculated F value for pressure $F = 1.6/12.0 = 0.13$

--Calculated F value for temperature $F = 22.1/12.0 = 1.84$

--Tabulated value for $F_{0.95}(3,9) = 3.86$

Conclusion: Neither pressure nor temperature variations have a significant effect on the regression intercept at the 0.95 confidence level.

Table 5. COMPARISON OF REGRESSION CONSTANTS FOR CALIBRATIONS OF A ROTAMETER WITH A ReF DEVICE

	Pressure (mmHg)			
	760	711	633	596
Temperature K	(slope, intercept)	(slope, intercept)	(slope, intercept)	(slope, intercept)
284	(36.76, -7.63)	(37.38, -12.93)	(39.47, -14.11)	(35.59, -10.26)
296	(36.03, -9.40)	(29.70, - 1.87)	(41.43, -19.34)	(30.45, - 3.40)
306	(34.01, -8.20)	(35.34, - 9.27)	(35.78, -13.28)	(32.82, - 7.44)
315	(32.60, -6.64)	(35.32, -10.84)	(31.09, - 3.63)	(34.79, -10.34)

Summary Statistics: $c_1 = 34.91$, $s_{c_1} = 3.14$; $d_1 = -9.29$, $s_{d_1} = 4.43$.

Table 6. COMPARISON OF REGRESSION CONSTANTS FOR CALIBRATIONS OF A PRESSURE TRANSDUCER WITH AN ORIFICE CALIBRATION UNIT

	Pressure (mmHg)			
	760	711	633	596
Temperature K	(slope, intercept)	(slope, intercept)	(slope, intercept)	(slope, intercept)
284	(1.01, -0.83)	(0.97, + 2.27)	(0.98, + 1.81)	--
296	(0.91, 4.61)	(1.02, - 0.26)	(1.07, - 2.61)	(0.99, + 1.17)
306	(1.02, 0.46)	(1.05, - 1.36)	(1.05, - 1.30)	—
315	—	(1.01, - 0.27)	(1.02, - 0.67)	(0.99, + 0.70)

Summary Statistics: $c_1 = 1.01$, $s_{c_1} = 0.04$; $d_1 = 0.29$, $s_{d_1} = 1.88$.

Table 7. COMPARISON OF REGRESSION CONSTANTS FOR CALIBRATIONS OF A PRESSURE TRANSDUCER WITH A ReF DEVICE

Temperature K	Pressure (mmHg) 760 (slope, intercept)	711 (slope, intercept)	633 (slope, intercept)	596 (slope, intercept)
284	(1.00, -0.37)	(1.05, - 5.07)	(0.98, + 0.41)	(1.04, -2.71)
296	(1.02, -2.41)	(1.14, - 8.99)	(0.97, + 1.90)	(1.03, -2.12)
306	(0.99, +0.05)	(0.96, + 1.77)	(1.03, - 2.41)	(1.01, -1.30)
315	(0.98, +1.43)	(1.08, - 1.82)	(0.97, + 0.28)	(1.02, -1.27)

Summary Statistics: $c_1 = 1.02$, $s_{c_1} = 0.05$; $d_1 = 1.42$, $s_{d_1} = 2.75$.

To further evaluate the assumption made in Section 3, namely, that the relationship between $Q_{theoretical}$ and I was of the form

$$Q_{theoretical} = c_1 I + b_1, \tag{67}$$

regressions of

$$Q_{theoretical} = c_5 (I)^{1/2} + b_5, \tag{68}$$

were calculated for the 16 rotameter calibrations performed using the orifice calibration unit.

For the 16 calibrations the average correlation coefficient for Equation (67) is 0.9952 compared to 0.9945 for Equation (68). This difference of 0.0007 is considered negligible, but it does show that, for this set of data, Equation (67) provides a slightly better fit for the data than does Equation (68).

Using the model

$$Q_{theoretical} = c_5 I^n + b_5 \tag{69}$$

with the 16 sets of calibration data, the best estimate of n was approximately 1.0; however, the response surface changes so gradually that any value of n between 0.5 and 1.0 results in an acceptable fit of the data.

Conclusions

Based on the experimental data presented in Tables 1 - 7, the hypothesis that a high volume sampler flow rate can be accurately predicted from rotameter (or pressure transducer) indications, over a wide range of ambient temperature and pressure conditions, by a linear regression equation of the form

$$Q_{theoretical} = c_1 I + d_1 \quad (1)$$

cannot be rejected. Thus it follows that the relationships

$$Q_{std} = c_2 I (P_b/T_a)^{1/2} + d_2 \quad , \quad (2)$$

and

$$Q_a = c_3 I (T_a/P_b)^{1/2} + d_3 \quad (3)$$

accurately predict the flow rate based on a standard volume Q_{std} and the flow rate at ambient conditions Q_a, respectively.

COMPARISON OF PRIMARY CALIBRATIONS

The purpose of this section is to give an example of primary calibrations of a secondary calibration device performed at two laboratories using different primary standards. The procedures were applied to both the orifice calibration unit and the ReF device. A primary calibration was accomplished in Denver, Colorado, in the EPA Regional laboratories using a Roots meter as the primary calibration device. A second calibration of the same orifice calibration unit was performed 3 days later in the QAB/EMSL laboratories with a different Roots meter.

Table 8 lists the data resulting from the first primary calibration in Denver. The barometric pressure P_b was 625 mmHg and the average ambient temperature T_a was 292 K during the calibration. Five resistance plates were inserted individually between the orifice calibration unit and the Roots meter. The motor was turned on after insertion of each plate. The volume V_m measured by the Roots meter was recorded over a time interval t which was measured with a stopwatch. Also recorded were the pressure drop from ambient to the opening of the Roots meter ΔP and the water manometer reading ΔH, which indicates the pressure drop across the orifice calibration unit.

The flow rate $Q_{theoretical}$ in m^3/min was calculated for each resistance plate using the following equation:

$$Q_{theoretical} = (V_m/t)\ [(P_b - \Delta P)/P_b]\ [(P_b/T_a)\ (T_{std}/P_{std})]^{1/2} \quad (70)$$

The results are listed in the seventh column of Table 8. A linear regression of $Q_{theoretical}$ on $(\Delta H)^{1/2}$ resulted in this equation:

$$Q_{theoretical}\ (OCU) = 0.498\ (\Delta H)^{1/2} - 0.003;\ r = 0.998\ . \quad (71)$$

In the same manner, the orifice calibration unit was again calibrated in the QAB/EMSL laboratories at a barometric pressure of 763 mmHg and an average ambient temperature of 297 K. These data are tabulated in Table 9. The calibration equation was calculated to be:

$$Q_{theoretical}\ (OCU) = 0.498\ (\Delta H)^{1/2} + 0.013;\ r = 0.994\ . \quad (72)$$

Table 10 shows calculated $Q_{theoretical}$ values for both regression equations over the normal flow rate range used in calibration. As shown in the last column of the table the Denver calibration results show a -2 percent bias over the flow rate range. This level of agreement is good when compared to results obtained from a collaborative test of the calibration method that showed the 95 percent confidence interval for the error associated with calibration of orifice calibration units to be ± 4.1 percent (2).

Applying the same procedure to the ReF device resulted in regression equations of

Denver: $Q_{theoretical}\ (ReF) = 0.497\ (\Delta H)^{1/2} + 0.004$, and (73)
RTI: $Q_{theoretical}\ (ReF) = 0.474\ (\Delta H)^{1/2} + 0.041$. (74)

Table 11 compares the two regression equations over a flow rate range of about 1 to 1.65 m^3/min and shows agreement within ± 1 percent. This is considered to be very good agreement.

Table 8. RESULTS FROM PRIMARY CALIBRATION OF ORIFICE CALIBRATION UNIT IN DENVER

Plate No.	V_m (m^3)	t (min)	P_b (mmHg)	T_a (K)	ΔP (mmHg)	$Q_{theoretical}$ (m^3/min)	ΔH (in . H_2O)
18	22.7	12.52	625	291	40	1.55	9.93
13	17.0	10.34	625	291	46	1.39	8.05
10	19.8	13,48	625	293	43	1.25	6.16
7	14.2	12.26	625	293	64	0.95	3.62
5	11.3	12.32	625	293	72	0.74	2.35

Table 9. RESULTS FROM PRIMARY CALIBRATION OF ORIFICE CALIBRATION UNIT IN RESEARCH TRIANGLE PARK

Plate No.	V_m (m^3)	t (min)	P_b (mmHg)	T_a (K)	Δ P (mmHg)	$Q_{theoretical}$ (m^3/min)	ΔH (in. H_2O)
18	19.0	10.38	763	297	44	1.66	11.25
13	17.0	10.66	763	297	51	1.51	9.10
10	17.0	11.90	763	297	51	1.32	6.17
7	16.0	14.03	763	297	70	1.04	4.39
5	10.0	11.17	763	297	80	0.80	2.63

Table 10. COMPARISON OF PRIMARY CALIBRATIONS OF ORIFICE CALIBRATION UNIT

	Calculated $Q_{theoretical}$ Values		Difference	
$(\Delta H)^{1/2}$ (in. $H_2O)^{1/2}$	Denver (m^3/min)	RTI (m^3/min)	m^3/min*	%†
2.0	0.99	1.01	-0.02	-2
2.5	1.24	1.26	-0.02	-2
3.0	1.48	1.51	-0.03	-2
3.4	1.68	1.71	-0.03	-2

*Difference = Denver - RTI

%†Difference = 100 (Denver - RTI)/RTI

Table 11. COMPARISON OF PRIMARY CALIBRATIONS OF ReF DEVICE

	Calculated $Q_{theoretical}$ Values		Difference	
$(\Delta H)^{1/2}$ (in. $H_2O)^{1/2}$	Denver (m^3/min)	RTI (m^3/min)	m^3/min*	%†*
2.0	1.00	0.99	0.01	1
2.5	1.23	1.23	0.00	0
3.0	1.45	1.46	-0.01	-1
3.4	1.63	1.65	-0.02	-1

*Difference = Denver - RTI

%†Difference = 100 (Denver - RTI)/RTI

COMPARISON OF SECONDARY CALIBRATION DEVICES

Throughout the experimental portion of this project two secondary calibration devices were used. One device was a calibration orifice unit used in the EPA reference method; the other was a ReF device used by QAB/EMSL in its auditing program.

The procedure used to compare the two secondary devices was to perform a primary calibration of both devices, then use each device alternately to calibrate a high volume sampler/rotameter system under as nearly identical conditions as possible.

Table 12 summarizes the calibration data over the range of temperature and pressure conditions tested in the study. Each regression equation in Table 12 was calculated using all the calibration data for that particular calibration device and flow indicator combination, i.e., they are average regression equations. (Average slopes and intercepts were taken from Tables 1, 3, 5, 6 and 7 and converted to metric units for OCU/rotameter, ReF/rotameter, OCU/PT and ReF/PT combinations, respectively.

As can be seen from Table 12, for a given rotameter or pressure transducer indication, the ReF device indicated a lower flow rate than the orifice calibration unit. When the rotameter was used as the flow indicator, the ReF device showed a constant negative difference of 0.115 m^3/min over the calibration range. The difference was in the same direction but much smaller when using the pressure transducer.

These data indicate that there is a difference between the two secondary calibration devices. However, when a pressure transducer is used the difference is negligible. The difference experienced when using the rotameter as the flow rate indicator is larger than desired for calibration devices and should be explored further.

Table 12. COMPARISON OF SECONDARY CALIBRATION DEVICES

Regression Equation	I (arbitrary)	$Q_{theor.}$(OCU) (m^3/min)	$Q_{theor.}$(ReF) (m^3/min)	Difference (m^3/min)	%
ROTAMETER					
Q_{theor} (OCU) =	1.25	1.10	0.98	-0.12	-11
0.98(I) - 0.26	1.50	1.34	1.23	-0.11	- 8
Q_{theor} (ReF) =	1.75	1.59	1.47	-0.12	- 8
0.99(I) - 0.26	2.00	1.83	1.72	-0.11	- 6
PRESSURE TRANSDUCER					
Q_{theor} (OCU) =	35.0	1.01	0.97	-0.04	- 4
.0286(PT)+.0082	45.0	1.30	1.26	-0.04	- 3
Q_{theor} (ReF) =	55.0	1.58	1.55	-0.03	- 2
.0289(PT)-.0402	65.0	1.87	1.84	-0.03	- 2

SECTION 5

FLOW RATE CALIBRATION AND DATA REPORTING PROCEDURES

The purpose of this section is to present technically sound flow rate calibration and data reporting procedures. These procedures are presented in a step-by-step fashion in sufficient detail to allow for direct use by field personnel. Specifically, this section contains a set of recommended calibration procedures followed by two alternate and totally acceptable procedures.

Use of the term "recommended procedures" is not meant to imply that these procedures are more technically correct than the alternate procedures, rather that this particular set of procedures is recommended because:

1. It simplifies the generation of primary and secondary calibration equations or plotted curves in situations where pocket calculators or computers are not available;
2. It is less subject to calculation error and does not require that temperature and pressure conditions at the time of the high volume sampler calibration be known.

Either one or the other of the alternate procedures will probably be preferred by organizations having computer facilities. The end result, i.e., measured TSP, will be the same regardless of which procedure is used.

Procedures are presented in this section; questions on derivations and/or theory should be referred to Section 3.

RECOMMENDED CALIBRATION AND MEASUREMENT PROCEDURES

The calibration and use of high volume samplers can be logically divided into three phases as follows:

phase 1-- calibration of the orifice calibration unit (secondary standard) with a Roots meter (primary standard), usually performed in the laboratory;

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phase 2-- calibration of the high volume sampler with the orifice calibration unit; performed in the field or in the laboratory.

phase 3-- use of high volume sampler in the field.

The three phases are illustrated in Figure 12. The solid dark lines in the figure represent the forward progression of the calibration process, while the dashed lines represent measurements from one phase that are used with the regression equation or graph developed in the previous phase to calculate or read a flow rate. Basically, the recommended procedures involve dealing with a theoretical flow rate referenced to 298 K and 760 mmHg during primary and secondary calibrations. Field temperature and pressure estimates, or measurements, are used to convert the theoretical flow rate to the flow rate of a standard volume Q_{std} at reference conditions of 298 K and 760 mmHg, and, if desired, to the actual flow Q_a at field (ambient) conditions.

Each of the three phases as described above is discussed separately in the following subsections.

Phase 1-- Calibration of the Orifice Calibration Unit

Calibration of an orifice calibration unit or other orifice like device is usually accomplished using a Roots meter as a primary standard. A typical laboratory calibration setup is shown in Figure 13. (For this calibration, voltage was held constant, and the flow rate was varied using resistance plates; it would have been just as valid to adjust the flow rate by varying the voltage.)

The apparatus required and parameters measured in performing a primary calibration include:

1. Roots meter--primary volume measurement, V_m;
2. Timer--sampling time, t;

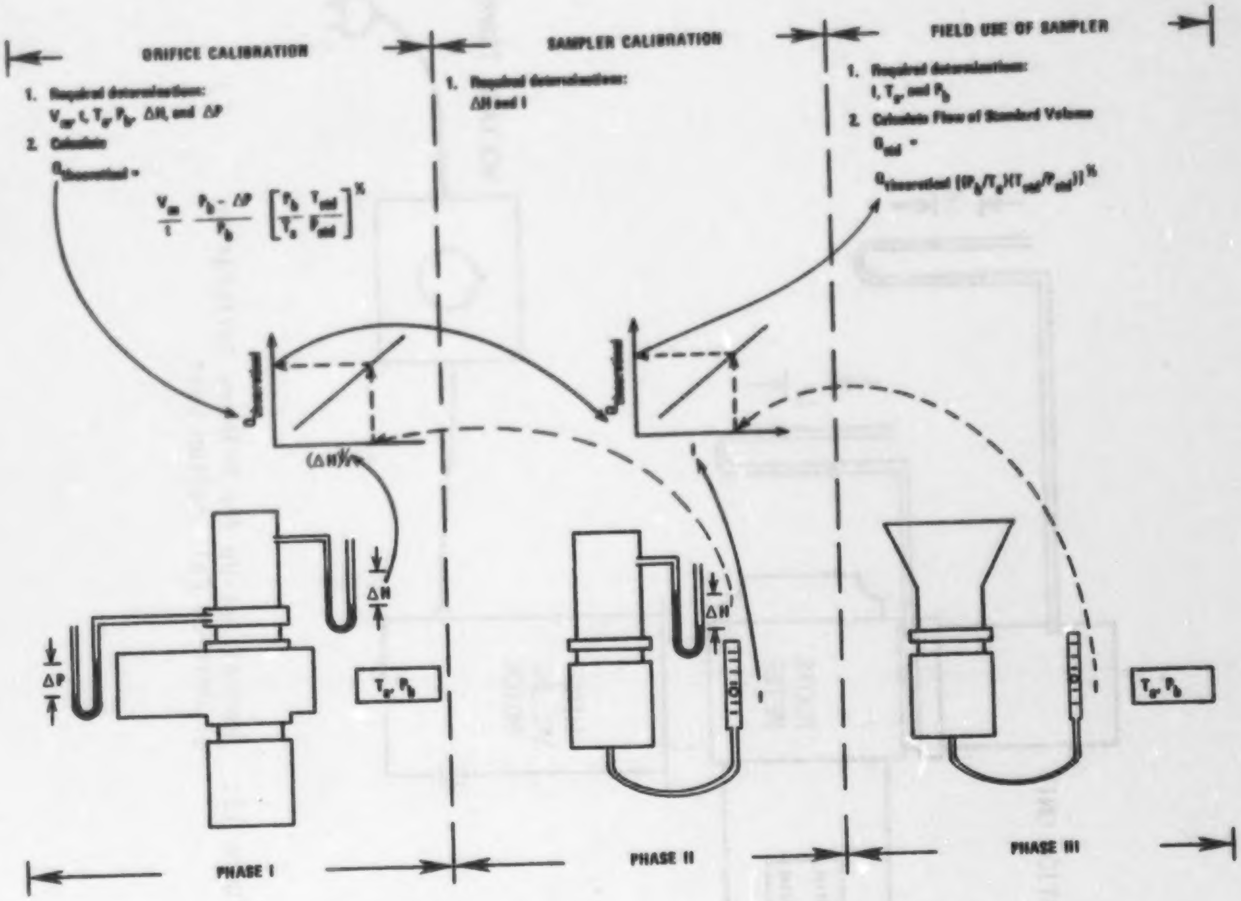
ORIFICE CALIBRATION
1. Required determinations:
V_m, t, T_a, P_b, ΔH, and ΔP
2. Calculate
$Q_{theoretical}$ =
$\frac{V_m}{t} \frac{P_b - \Delta P}{P_b} \left[\frac{P_b}{T_a} \frac{T_{std}}{P_{std}}\right]^{1/2}$
SAMPLER CALIBRATION
1. Required determinations:
ΔH and I
FIELD USE OF SAMPLER
1. Required determinations:
I, T_a, and P_b
2. Calculate Flow of Standard Volume
Q_{std} =
$Q_{theoretical} [(P_b/T_a)(T_{std}/P_{std})]^{1/2}$
$Q_{theoretical}$
$Q_{theoretical}$
$(\Delta H)^{1/2}$
ΔP
ΔH
ΔH
T_a, P_b
T_a, P_b
PHASE I
PHASE II
PHASE III

Figure 12. Illustration of recommended flow rate calibration and measurement process.

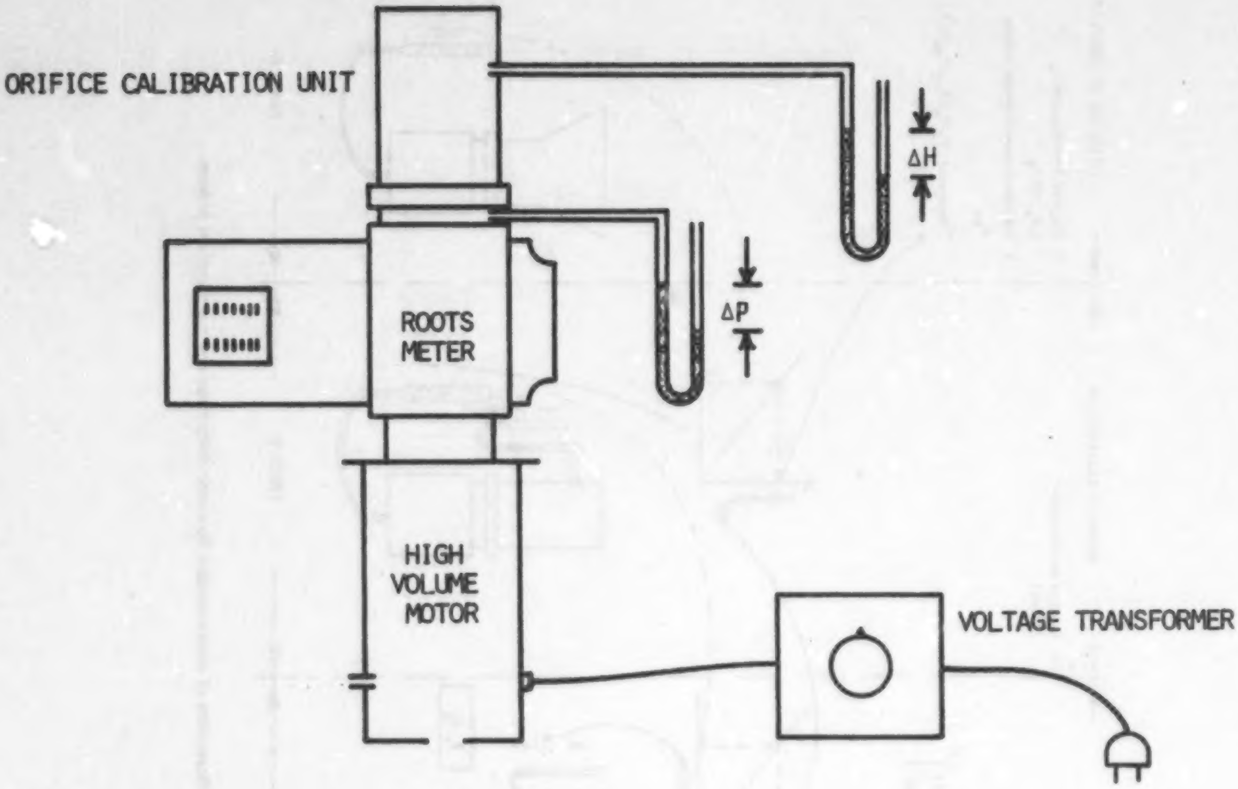
ORIFICE CALIBRATION UNIT
ΔH
ΔP
ROOTS METER
HIGH VOLUME MOTOR
VOLTAGE TRANSFORMER

Figure 13. Typical Set-Up for Primary Calibration of Orifice Calibration Unit

3. Two water manometers or other suitable pressure sensors—pressure drop across the orifice of the orifice calibration unit, ΔH, and the differential pressure (ambient - Roots meter inlet pressure), ΔP.

The procedure for calibration of an orifice calibration unit and an example treatment of calibration data are presented in the following two subsections.

Calibration Procedures (Phase I). Figure 14 is an example of a primary calibration worksheet. In this example, orifice calibration unit No. II is calibrated using Roots Meter No. 12-14-87 as recorded in Figure 14 in the block titled RECORDED CALIBRATION DATA. The barometric pressure P_b and ambient temperature T_a (item numbers 8 and 9 in Figure 14) were 754 mmHg and 295 K (22°C), respectively, at the time of the primary calibration.

For this calibration a fixed sampling or run time of 3.0 minutes (item 3) was employed with the Roots meter reading in m^3 read at the start (item 1) and at the end (item 2) of each run.

The pressure drop across the orifice (item 6) was read and recorded in inches of H_2O and the differential pressure from ambient to that at the inlet of the Roots meter (item 5) was read in inches Hg and converted to mmHg by multiplying by 25.4 mm/inch.

From the above recorded data a calibration equation and/or calibration curve is generated as follows:

1. Calculate the volume of air measured by the Roots meter for each run as the difference between the Roots meter readings at the start and finish of the test run. That is,

$$V_m = (2) - (1)$$

as shown in Figure 14 in the block titled CALCULATION EQUATIONS. Values of V_m are recorded in item 4 to the nearest 0.01 m^3.

2. Correct the volume V_m measured by the Roots meter at meter conditions of T_m and P_m to the volume V_a passing through the orifice (orifice calibration unit) at ambient conditions of T_a and P_b by

PRIMARY CALIBRATION WORKSHEET

Run No.	(1) Meter Reading Start (m^3)	(2) Meter Reading Stop (m^3)	(3) Sampling Time t (min)	(4) Volume Measured by Meter V_m=(2)-(1) (m^3)	(5) Differential Pressure (Ambient-Meter) ΔP (mmHg)	(6) Pressure Drop Across Calibration Orifice ΔH (in.H_2O)	(7) Flow Rate $Q_{theoretical}$ m^3/min
1	264.63	269.80	3.00	5.17	36.8	10.00	1.64
2	272.97	277.70	3.00	4.73	44.5	8.27	1.49
3	283.69	287.97	3.00	4.28	50.8	6.77	1.33
4	288.29	291.66	3.00	3.37	61.0	4.06	1.03
5	291.92	294.56	3.00	2.64	64.8	2.52	0.81

RECORDED CALIBRATION DATA

Roots Meter No. 12-14-87
Calibrator:
  Model No. Orifice Calibration Unit
  Serial No. II
(8) P_b: 754mmHg (10) P_{std}: 760 mmHg
(9) T_a: 295 K (11) T_{std}: 298 K
Calibration Performed By: J. Smith
Date: 7/7/77

CALCULATION EQUATIONS

$$V_m = (2) - (1)$$

$$Q_{theoretical} = \frac{V_m}{t} \frac{P_b - \Delta P}{P_b} \left[\left(\frac{P_b}{T_a}\right) \left(\frac{T_{std}}{P_{std}}\right) \right]^{1/2}$$

$$(7) = \frac{(4)}{(3)} \quad \frac{(8)-(5)}{(9)} \left[\frac{(8)}{(9)} \quad \frac{(11)}{(10)} \right]^{1/2}$$

REGRESSION EQUATION OF $Q_{THEORETICAL}$ ON $(\Delta H)^{1/2}$ FOR ORIFICE CALIBRATION UNIT AT 298 K AND 760 mmHg

$Q_{theoretical} = a_1 \, (\Delta H)^{1/2}$

$Q_{theoretical} = 0.527 \, (\Delta H)^{1/2} - 0.031$: $Q_{theoretical}$ (m^3/min), ΔH (in. H_2O)

Correlation coefficient (r): 0.999

Figure 14. Example of orifice calibration unit calibration worksheet.

$$V_a/t = (V_m/t)\ (P_m/T_m)\ (T_a/P_b) \quad . \qquad (75)$$

Generally, it is assumed that $T_a = T_m$. The actual volumetric flow rate through the orifice at T_a and P_b and for a pressure drop across the orifice of ΔH is calculated by

$$Q_a = V_a/t = V_m/t\ (P_b - \Delta P)/P_b \quad , \qquad (76)$$

where $P_m = P_b - \Delta P$.

The flow rate Q_a is the actual flow rate through the orifice at T_a and P_b for a specific pressure drop ΔH across the orifice.

3. Calculate the flow rate ($Q_{theoretical}$) that would be required at reference conditions, i.e., T_{std} = 298 K (25°C) and P_{std} = 760 mmHg, to maintain the same ΔH value as above by

$$Q_{theoretical} = Q_a\ [(P_b/T_a)\ (T_{std}/P_{std})]^{1/2} \quad . \qquad (4)$$

Caution: This is a flow correction for a fixed ΔH value, hence the orifice relationship of the form $Q_2 = Q_1\ [(P_1/T_1)\ (T_2/P_2)]^{1/2}$ must be used.

Record in Column 7 of Figure 14.

4. Summary. Steps 1 through 3 can be combined and, with the values T_{std} = 298 K and P_{std} = 760 mmHg plugged into Equation (4), the following relationship results

$$Q_{theoretical} = 0.626\ (V_m/t)\ (P_b - \Delta P)/\ (P_b \times T_a)^{1/2} \quad . \qquad (77)$$

If a regression equation is to be calculated, continue to step 5. However, if the data are to be graphed, go directly to step 6.

5. Calculate a least squares linear regression of $Q_{theoretical}$ on $(\Delta H)^{1/2}$, using the calculated $Q_{theoretical}$ value for each run (five in this case). The regression equation calculated for the data given in Figure 14 is shown in the lower right hand box titled REGRESSION OF $Q_{THEORETICAL}$ ON $(\Delta H)^{1/2}$ FOR ORIFICE CALIBRATION UNIT.

Note: An acceptable primary calibration consisting of five points should yield a correlation coefficient of $r \geq 0.995$ and have no data point ($Q_{theoretical}$ calculated from equation 77) deviating more than ± 0.04 m^3/min (1.4 ft^3/min) from the flow rate predicted by the regression equation for the same value of ΔH.

6. Construct a calibration curve of $Q_{theoretical}$ versus ΔH. The primary objective here is to fit the data points with a smooth curve. If the user prefers a straight line plot, he could graph $Q_{theoretical}$ versus ΔH on log log paper (a slope of 0.5 should result) or $Q_{theoretical}$ versus $(\Delta H)^{1/2}$ on linear graph paper.

   Figure 15 is an example plot of $Q_{theoretical}$ versus ΔH on linear graph paper. This method is recommended because of its simplicity in plotting and ease of reading. Figure 15 is representative of the graph illustrated in Phase 1 of Figure 12.

   The smallest division on the ordinate ($Q_{theoretical}$ axis) should be 0.01 m^3/min (0.35 ft^3/min) and on the abscissa (ΔH axis) it should be 0.1 in. H_2O.

Example treatment of calibration data (Phase I). For each run of a calibration, a value of $Q_{theoretical}$ must be calculated from the intermediate measurements made and recorded on the primary calibration work sheet. The data recorded for run 1 in Figure 14 is used here in an example calculation. (These calculation steps are illustrated in Figure 14 in the block titled CALCULATION EQUATIONS.)

1. Calculate the volume of air V_m measured by the Roots meter as the difference in the start (1) and stop (2) meter readings.

$$V_m = (2) - (1)$$
$$V_m = 269.80 - 264.63$$
$$V_m = 5.17 \text{ m}^3$$

   The volume V_m is recorded in column (4) of Figure 14.

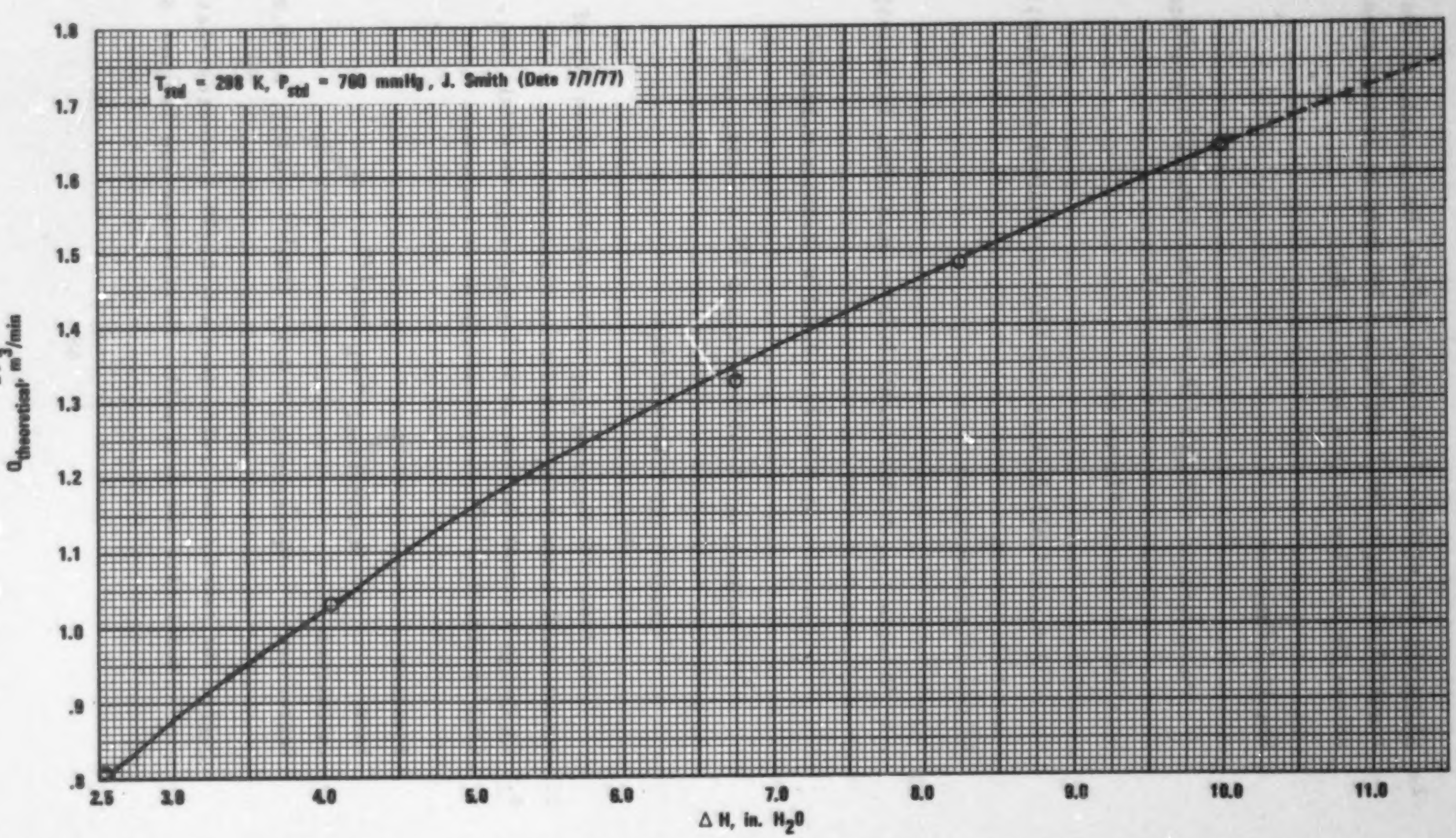

Figure 15. Example of calibration curve for an orifice calibration unit (data from Figure 14).

2. **Calculate** the orifice flow rate in m^3/min ($Q_{theoretical}$) that would be required at $T_{std} = 298$ K and $P_{std} = 760$ mmHg to yield a pressure drop across the orifice of $\Delta H = 10.00$ in. H_2O.

Required Equation

$$Q_{theoretical} = (V_m/t)\ [(P_b - \Delta P)/P_b]\ [(P_b/T_a)\ (T_{std}/P_{std})]^{1/2} \quad (78)$$

Location of data in Figure 14

$$(7) = [(4)/(3)]\ [((8) - (5))/(8)]\ [((8)/(9))\ ((11)/(10))]^{1/2}$$

Actual data in equation

$$Q_{theoretical} = (5.17/3.00)\ [(754 - 36.8)/754]\ [(754/295)\ (298/760)]^{1/2}$$

$$Q_{theoretical} = 1.723 \times 0.951 \times [2.556 \times 0.392]^{1/2}$$

$$Q_{theoretical} = 1.639 \times (1.002)^{1/2} = 1.639 \times 1.001$$

$$Q_{theoretical} = 1.64\ m^3/min$$

The flow rate $Q_{theoretical}$ is recorded in column (7) of Figure 14.

3. Repeat steps 1 and 2 for runs 2-5 in Figure 14.
4. **Calculate** a linear regression of $Q_{theoretical}$ in m^3/min on $(\Delta H)^{1/2}$ (in. $H_2O)^{1/2}$ using a calculator or computer.

Equation Form	$Q_{theoretical} = a_1\ (\Delta H)^{1/2}$	(40)
Calculated Regression	$Q_{theoretical} = 0.527\ (\Delta H)^{1/2} - 0.031;\ r = 0.999$	(79)

Note: The correlation coefficient r = 0.999 indicates that a linear model fits the data well. In this case the largest difference between calculated flows (column 7 of Figure 14) and those predicted by the regression equation for the same ΔH value is 0.01 m^3/min, which is less than 1 percent of the actual value at all except the lowest flow (0.81 m^3/min).

5. Construct a calibration curve. If a calibration graph is preferred over a regression equation for use in future high volume sampler calibrations, a plot such as that in Figure 15 should be constructed.

   It is recommended that the actual data points be included on the graph along with the values of T_{std} and P_{std}.

Caution: At this point $Q_{theoretical}$ is a flow rate referenced to standard conditions; it is not the flow rate of a standard volume and should not, for example, be reported as std m^3/min.

Phase II--Calibration of High Volume Sampler

Phase II as illustrated in Figure 12 involves the use of the orifice calibration unit data, either regression equation or graph, generated in Phase I to develop a high volume sampler calibration.

For the procedure recommended here, the only measurements required in calibrating the sampler are: (a) the pressure drop across the orifice, ΔH, for a fixed flow rate, and (b) the indication I on the sampler flow rate indicator (a rotameter was used in this example). Ambient temperature and pressure measurements are not required for the high volume sampler calibration.

Calibration Procedures. Figure 16 is an example high volume sampler calibration data sheet.

With the configuration as shown in Phase II of Figure 12, corresponding ΔH and I values are recorded for each of a series of constant but different flow rates (runs) as illustrated in Figure 16.

Each ΔH reading for the five runs is used to determine the flow rate ($Q_{theoretical}$) using either the regression equation or the calibration curve developed in Phase I for the orifice calibration unit.

HIGH VOLUME SAMPLER CALIBRATION DATA SHEET

High Volume Sampler No. 123 Calibrator Model No. OCU Date: 7/8/77

Calibrated By: J. Smith Serial No. II Location: RTI Campus

Run No.	Ambient Temp. T_a (K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Orifice ΔH (in.H_2O)	Flow Rate Indication I (Arbitrary)	Flow Rates From Orifice* Calibration $Q_{Theoretical}$	
					(m^3/min)	(ft^3/min)
1	280	758	(11.4)	1.85	1.75	(61.8)
2	280	758	(8.5)	1.68	1.51	(53.3)
3	280	758	(7.1)	1.50	1.37	(48.4)
4	280	758	(4.6)	1.28	1.10	(38.8)
5	280	758	(2.9)	1.05	0.87	(30.7)

* Orifice calibration equation $Q_{Theoretical} = 0.527(\Delta H)^{1/2} - 0.031$ (See Figure 14 or Graph 15)

REGRESSION OF $Q_{Theoretical}$ ON I

$Q_{Theoretical} = c_1 I + d_1$

$Q_{Theoretical} = 1.084 I - 0.276$: $r = 0.998$

Figure 16. Exampler of high volume sampler calibration data sheet.

A linear regression equation of $Q_{theoretical}$ on I is calculated for the high volume sampler, or a plot of $Q_{theoretical}$ versus I is constructed as in Figure 17.

Again, as for the orifice calibration, an acceptable high volume sampler calibration of five points should yield a regression equation with a correlation coefficient of $r > 0.990$ with no point deviating more than ±0.04 m^3/min from the value predicted by the regression equation.

Example calculation. One strong reason for recommending this particular calibration procedure is that the calculation requirements for this phase, which is usually carried out in the field, are minimal.

Taking the data for run 1 as recorded in Figure 16, the required calculations are as follows:

1. Calculate the flow rate ($Q_{theoretical}$) for $\Delta H = 11.4$ using the regression equation for the orifice calibration unit as developed in Phase I.

   Regression Equation $$Q_{theoretical} = 0.527 \quad \Delta H^{1/2} - 0.031$$

   $$Q_{theoretical} = 0.527 \quad (11.4)^{1/2} - 0.031$$

   $$Q_{theoretical} = 1.75 \ m^3/min$$

   or

2. Read from the calibration curve in Figure 15 as developed in Phase I. From the graph a ΔH value of 11.4 yields a flow rate of

   $$Q_{theoretical} = 1.75 \ m^3/min \ .$$

3. Repeat Step 1 or 2, as applicable, for each run. Record the flow rate values with the corresponding ΔH values in Figure 16.

4. Compute a linear regression of $Q_{theoretical}$ on I using the five data pairs.

For the data in Figure 16 the resulting regression equation is

$$Q_{theoretical} = c_1\ I + b_1$$

$$Q_{theoretical} = 1.084\ I - 0.276$$

$$\text{correlation coefficient:}\quad r = 0.998$$

or

5. Construct a calibration curve of $Q_{theoretical}$ versus I on linear graph paper as shown in Figure 17. The calibration curve should be dated and signed by the individual who performed the calibration. Actual data points should be plotted on the graph, and values of T_{std} and P_{std} indicated.

   Figure 17 is an actual high volume sampler calibration curve as opposed to the illustrated calibration curve in Phase II of Figure 12.

Phase III--Field Use of High Volume Sampler

Field use of the high volume sampler, referred to here as Phase III, is illustrated in Figure 12. Four determinations are required during sample collection in order to calculate the volume of air sampled and to correct that volume to reference conditions. Those four determinations are: (a) average flow rate ($Q_{theoretical}$) for the sampling period, (b) sampling period time t, (c) average ambient temperature T_a during the sampling period, and (d) average barometric pressure P_b during the sampling period. Three determinations (I, T_a, and P_b) are required to calculate the standard or actual flow rate (Figure 12).

The first two measurements, average flow rate and sampling period time, are the most important and require on-site measurement. We believe that for a given sampling site the temperature and pressure can be measured or adequately approximated in any of several ways (See "Recommendations" in Section 2).

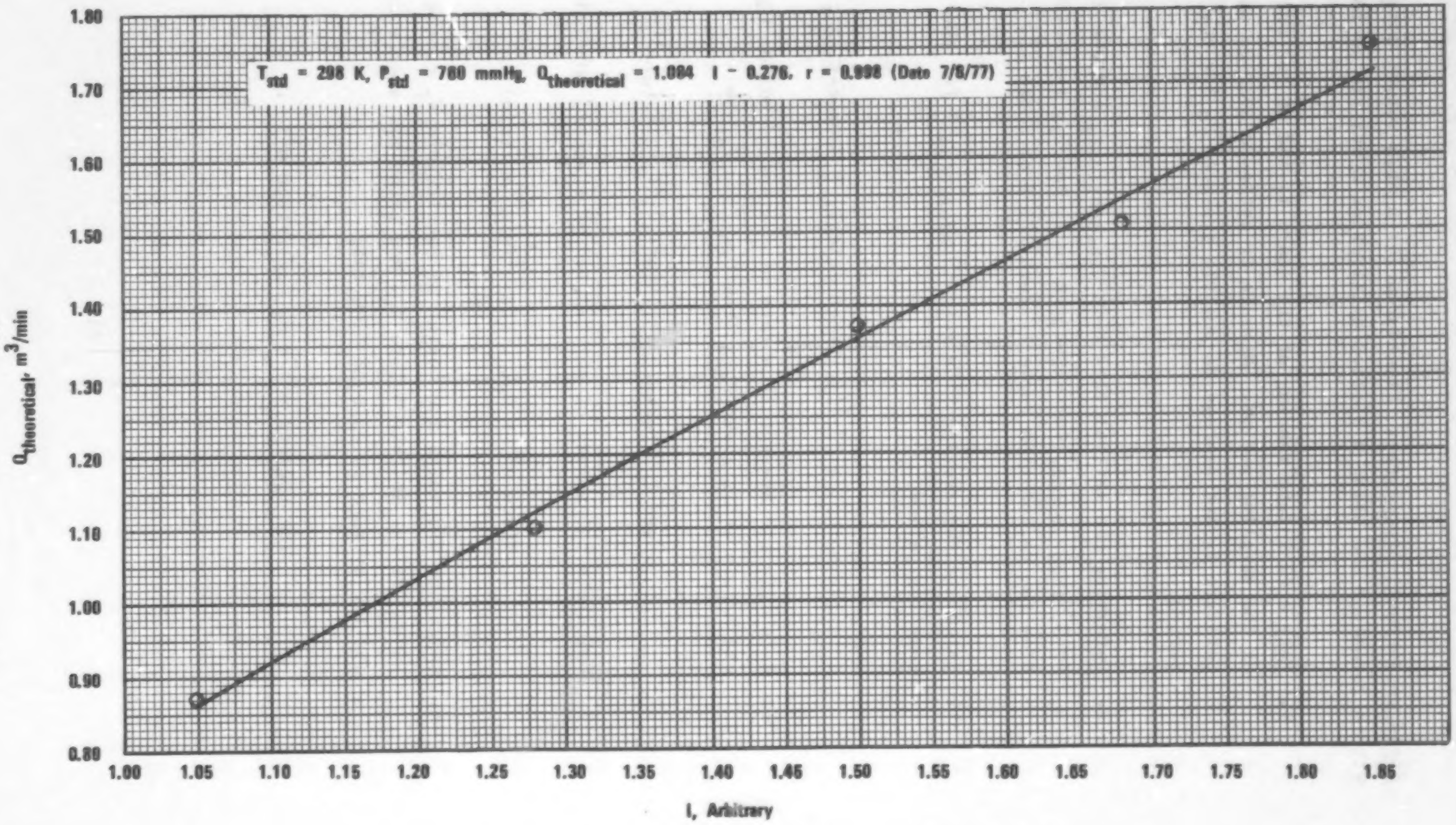

Figure 17. Example of high volume sampler flow rate calibration sheet.

Field measurement procedures. Procedures for a high volume sampler equipped with a rotameter and using a plotted calibration curve are as follows:

1. Make a flow rate reading at the start I_i and at the end I_f of the of the sampling period. Measure or estimate average ambient temperature T_a and average barometric pressure P_b for the sampling period.

2. Determine the initial flow rate $Q_{theoretical_i}$ and the final flow rate $Q_{theoretical_f}$ corresponding to I_i and I_f, respectively, from the calibration curve (Figure 17) from Phase II.

3. Calculate the average flow rate ($Q_{theoretical}$) for the sampling sampling period

$$Q_{theoretical} = 1/2\ (Q_{theoretical_i} + Q_{theoretical_f}) \ .$$

4. Calculate the average flow rate of a standard volume (Q_{std}) in std m^3/min at T_{std} and P_{std} from $Q_{theoretical}$ by

$$Q_{std} = Q_{theoretical}\ [(P_b/T_a)\ (T_{std}/P_{std})]^{1/2} \ . \qquad (79)$$

5. Calculate the volume of air sampled at standard conditions as

$$V(\text{std m}^3) = Q_{std}\ (\text{std m}^3/\text{min}) \times t(\text{min}) \ .$$

6. Calculate TSP using the weight of particulate W_p as the difference in the filter weights before W_i, and after W_f, sample collection and the average calculated flow rate

$$\text{TSP}\ (\mu g/\text{std m}^3) = W_p\ (\mu g)/V(\text{std m}^3) \ . \qquad (80)$$

Example calculation. As an example let us assume that for a given sampling period the following measurements were recorded

$I_i = 1.70$ $T_a = 273$ K (0°C) $t = 1440$ min

$I_f = 1.65$ $P_b = 670$ mmHg

Also, from gravimetric analysis of the filter, the resulting particulate catch was

$$W_p = W_f - W_i = 100{,}000\ \mu g \quad .$$

Following the same sequence outlined in the previous sections, the calculations are:

1. Reading from the graph in Figure 17

   $I_i = 1.70 \quad Q_{\text{theoretical}_i} = 1.535\ m^3/\text{min}$, and

   $I_f = 1.65 \quad Q_{\text{theoretical}_f} = 1.570\ m^3/\text{min}$.

2. Calculate the average flow rate $Q_{\text{theoretical}}$ (rounded to 0.01 m^3/min)

$$Q_{\text{theoretical}} = 1/2\ (Q_{\text{theoretical}_i} + Q_{\text{theoretical}_f})$$

$$Q_{\text{theoretical}} = 1/2\ (1.535 + 1.570)$$

$$Q_{\text{theoretical}} = 1.55\ m^3/\text{min at STP} \quad .$$

3. Calculate the average flow rate of a standard volume Q_{std} from $Q_{\text{theoretical}}$ by

$$Q_{\text{std}} = Q_{\text{theoretical}}\ [(P_b/T_a)\ (T_{\text{std}})/P_{\text{std}})]^{1/2}$$

$$Q_{\text{std}} = 1.55\ (m^3/\text{min})\ [(670/273)\ (298/760)]^{1/2}$$

$$Q_{\text{std}} = 1.52\ \text{std}\ m^3/\text{min} \quad .$$

4. Calculate the volume of air sampled at standard conditions as

$$V = Q_{std} \times t$$

$$V = 1.52 \text{ std m}^3/\text{min} \times 1440 \text{ min}$$

$$V = 2189 \text{ std m}^3 \quad .$$

5. Calculate TSP by

$$\text{TSP } (\mu\text{g/std m}^3) = W_p\ (\mu\text{g})/V\ (\text{std m}^3)$$

$$\text{TSP} = 100{,}000\ \mu\text{g}/2189 \text{ std m}^3$$

$$\text{TSP} = 457\ \mu\text{g/std m}^3 \quad .$$

Note: It is assumed that the intent of the directive (6) that all ambient air quality data must be referenced to standard conditions of 25°C and 760 mmHg was to have all data based on a standard volume, either std m^3 or std ft^3, at those conditions.

6. If for some requirement of the project the TSP data are required to be based on the actual volume, V_a, sampled at field conditions the calculation is as follows

$$V_a(\text{m}^3) = Q_a(\text{m}^3/\text{min})\ t(\text{min})\ [(T_a/P_b)\ (P_{std}/T_{std})]^{1/2}$$

$$V_a\ (\text{m}^3) = (1.55 \times 1440)\ [(273/670)\ (760/298)]^{1/2}$$

$$V_a = 2275 \text{ m}^3 \text{ at } T_a,\ P_b$$

and

$$\text{TSP } (\mu\text{g/m}^3) = W_p\ (\mu\text{g})/V_a(\text{m}^3) = 100{,}000\ \mu\text{g}/2275 \text{ m}^3$$

$$\text{TSP} = 440\ \mu\text{g/m}^3 \text{ at } T_a = 0°\text{C and } P_b = 670 \text{ mmHg} \quad .$$

ALTERNATE PROCEDURES

As previously stated, the procedures discussed in the previous subsection were recommended because of their simplicity, especially when graphical techniques are used. Two alternate procedures are summarized here. Both of these procedures are as technically correct as the recommended procedures. Either of these alternate procedures would have been selected over the recommended procedure if we believed that most field personnel were well versed in the use of calculators or computers in performing regression analysis.

Two procedures are discussed here. One procedure involves calibrating the orifice calibration unit and then the high volume sampler using the actual flow rate Q_a and converting to the flow rate of a standard volume Q_{std} as the final step in calculating TSP. The second procedure involves working with the flow rate of a standard volume Q_{std} throughout the three phases of the calibration and measurement process.

Calibration Procedure Using Actual Flow Rates

Following somewhat the same sequence of steps given for the recommended procedures, the procedure based on the actual flow rate is illustrated in Figure 18 and discussed below.

Phase I Calibration of the Secondary Standard

1. Calculate the actual flow rate Q_a through the orifice for a given ΔH value using the volume V_m measured by the Roots meter and the time in minutes t of the sample run by

$$Q_a = (V_m/t)\ [(P_b - \Delta P)/P_b]\ (T_a/T_m) \quad . \tag{81}$$

A usual assumption made is that $T_a \doteq T_m$, thus

$$Q_a = (V_m/t)\ \ (P_b - \Delta P)/(P_b) \quad . \tag{39}$$

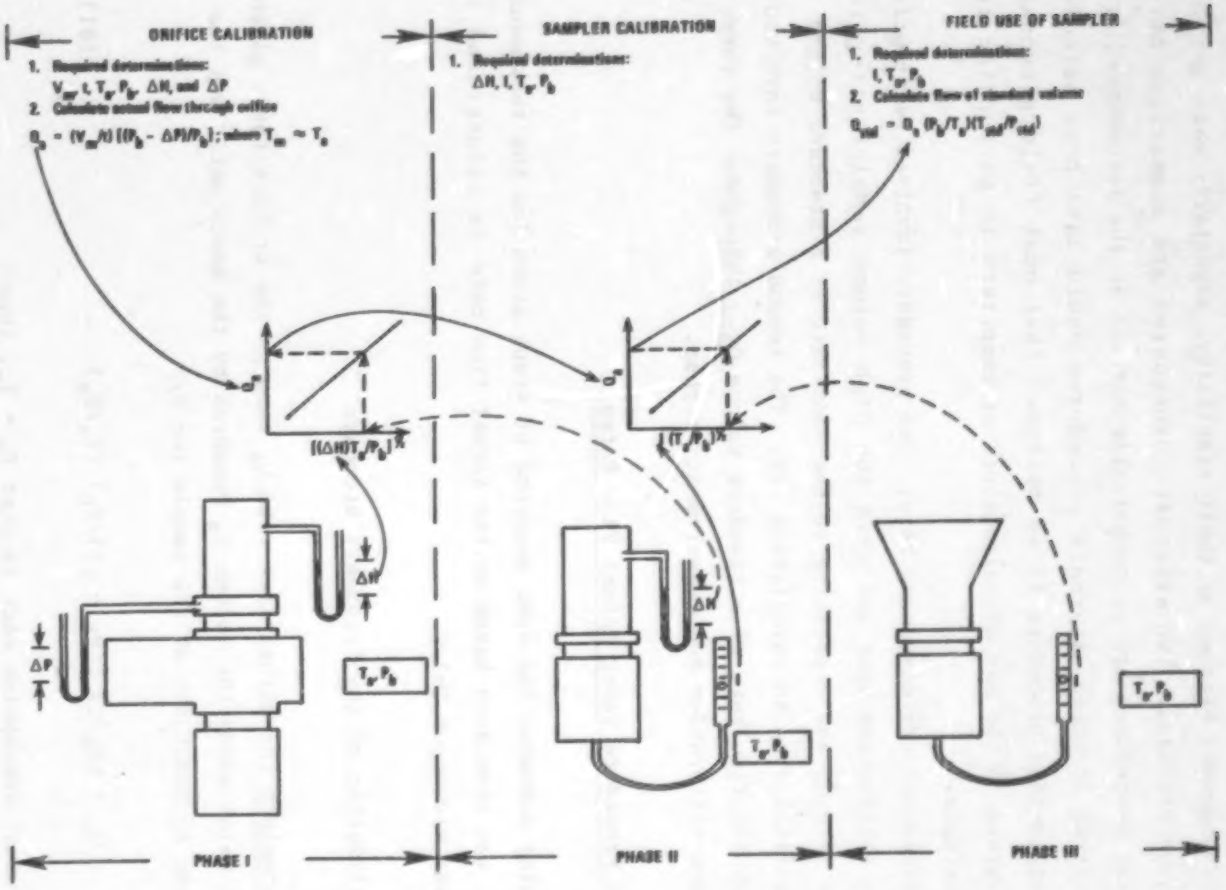
ORIFICE CALIBRATION
1. Required determinations:
V_{m}, t, T_a, P_b, ΔH, and ΔP
2. Calculate actual flow through orifice
$Q_a = (V_m/t)[(P_b - \Delta P)/P_b]$; where $T_m \approx T_a$
SAMPLER CALIBRATION
1. Required determinations:
ΔH, I, T_a, P_b
FIELD USE OF SAMPLER
1. Required determinations:
I, T_a, P_b
2. Calculate flow of standard volume
$Q_{std} = Q_a (P_b/T_a)(T_{std}/P_{std})$
Q_a
$[(\Delta H)T_a/P_b]^{1/2}$
Q_a
$I(T_a/P_b)^{1/2}$
ΔP
ΔH
T_a, P_b
ΔH
T_a, P_b
T_a, P_b
PHASE I
PHASE II
PHASE III

Figure 18. Illustration of actual flow rate calibration and measurement process.

2. Repeat step one for each run (five in this case, as shown in Figure 12).

3. Calculate a linear regression of Q_a on $(\Delta H\ T_a/P_b)^{1/2}$ using the data pairs from the five runs. In lieu of calculating a regression equation, a plot of Q_a versus $(\Delta H\ T_a/P_b)^{1/2}$ could be made on linear graph paper. For the orifice calibration unit the regression equation is of the form

$$Q_a = a_3[(\Delta H)T_a/P_b]^{1/2} \quad . \tag{42}$$

Note: Again the main objective is to accurately fit the data over the range that the relationship is to be used. Thus if other models provide an acceptable fit over the desired range, there is nothing wrong with using them. Also, if the zero intercept model yields acceptable results, use it; however, it should be tested against the intercept model prior to its use for a specific orifice calibration unit.

Phase II Calibration of High Volume Sampler

4. Calibration of the High volume sampler requires measures of pressure drop ΔH across the orifice, sampler flow indication I on the rotameter, ambient temperature T_a and barometric pressure P_b.

5. Calculate Q_a for each calibration run using Equation (42) for the orifice calibration unit.

6. Calculate a linear regression of Q_a on $I\ (T_a/P_b)^{1/2}$ using the five data pairs of Q_a and I. The resulting equation is of the form

$$Q_a = c_3\ I\ (T_a/P_b)^{1/2} + d_3 \quad . \tag{3}$$

As in step 3 of Phase I, if preferred, a plot of Q_a versus $I\ (T_a/P_b)^{1/2}$ would be constructed.

Phase III Use of the sampler in the field

7. Calculate the actual flow rate in the field for a rotameter indication I, an ambient temperature T_a, and a barometric pressure P_b, using the above high volume sampler regression equation or by reading from the graph of the calibration curve.

8. Convert the actual flow rate Q_a to the flow rate of a standard volume Q_{std} by

$$Q_{std} = Q_a \, (P_b/T_a)(T_{std}/P_{std}) \quad . \tag{29}$$

Note: At this point we are making a volume correction independent of the orifice calibration unit, thus the gas law relationship of the form

$$V_1P_1/T_1 = V_2P_2/T_2 \tag{82}$$

is used. Q_{std} is then in std m^3/min (or std ft^3/min if in English units).

9. Calculate TSP at standard reference conditions by

$$TSP = W_p \, (\mu g)/[Q_{std}(\text{std } m^3/\text{min} \times t \text{ (min)})] \quad .$$

Calibration Procedure Using the Flow Rate of a Standard Volume

If all TSP data are to be reported to EPA referenced to standard conditions, then working with the flow rate of a standard volume is the most straightforward procedure to use. Each of the three phases is illustrated in Figure 19. The procedure is as follows:

Phase I Calibration of the orifice calibration unit

1. Correct the flow rate based on the volume V_m measured by the Roots meter to the flow rate of a standard volume for each calibration run by

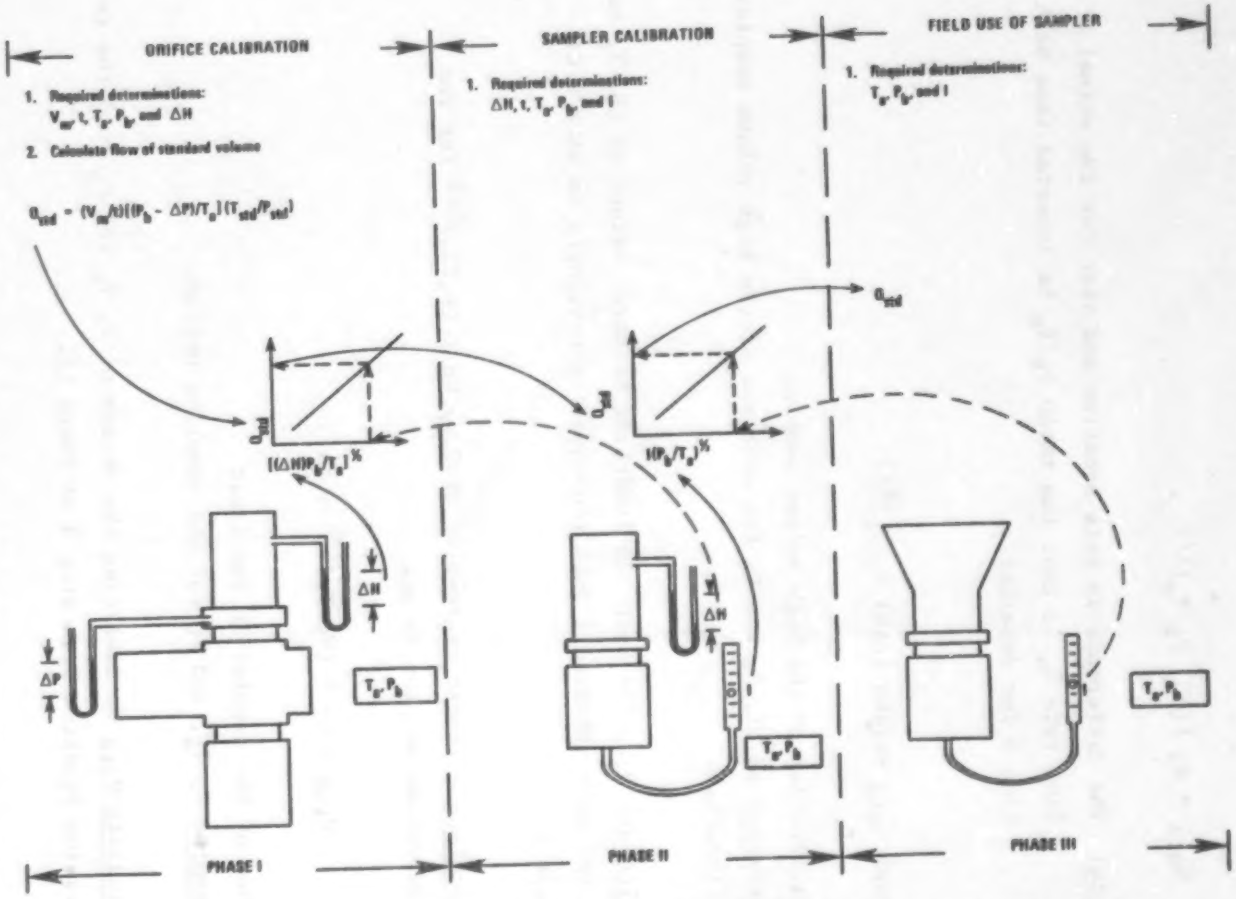
ORIFICE CALIBRATION
1. Required determinations: V_m, t, T_a, P_b, and ΔH
2. Calculate flow of standard volume
$Q_{std} = (V_m/t)[(P_b - \Delta P)/T_a](T_{std}/P_{std})$
SAMPLER CALIBRATION
1. Required determinations: ΔH, t, T_a, P_b, and I
FIELD USE OF SAMPLER
1. Required determinations: T_a, P_b, and I
Q_{std}
$[(\Delta H)P_b/T_a]^{1/2}$
Q_{std}
$I(P_b/T_a)^{1/2}$
Q_{std}
ΔP
ΔH
T_a, P_b
ΔH
I
T_a, P_b
I
T_a, P_b
PHASE I
PHASE II
PHASE III

Figure 19. Illustration of flow rate of a standard volume calibration and measurement process.

$$Q_{std} = (V_m/t)\ \ (P_b - \Delta P)/T_a\ \ (T_{std}/P_{std})$$

2. Calculate a linear regression of Q_{std} on $[(\Delta H\ P_b/T_a]^{1/2}$ to get

$$Q_{std} = a_2\ [(\Delta H)\ P_b/T_a]^{1/2}\ \ ,$$

Note: The difference in this equation and that for the actual flow rate Q_a is that the ratio P_b/T_a is inverted (see Section 3 for details).

or

3. Graph Q_{std} versus $[(\Delta H)\ P_b/T_a]^{1/2}$.

Phase II Calibration of the high volume sampler

1. Determine ΔH, I, T_a and P_b for each run of the high volume sampler calibration.

2. Calculate Q_{std} for each run inserting measured values of ΔH, T_a and P_b for each observed I into the equation developed in step 2 of Phase I.

3. Calculate a linear regression of Q_{std} on I $(P_b/T_a)^{1/2}$ for the high volume sampler to get

$$Q_{std} = c_2\ I\ (P_b/T_a)^{1/2} + d_2\ \ .$$

Phase III Use of the sampler in the field

1. Determine I, T_a, and P_b for the sampling period.

2. Calculate Q_{std} by inserting the values of I, T_a and P_b into the regression equation from step 3 of Phase II.

3. Calculate TSP at standard reference conditions by

$$\text{TSP}\ (\mu g/\text{std}\ m^3) = W_p\ (\mu g)/[Q_{std}\ (\text{std}\ m^3/\text{min})\ t\ (\text{min})]\ \ .$$

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APPENDIX A

Orifice Calibration Unit and Rotameter Calibration Data

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 8929 Calibrator Type: Orifice Cal Unit Date: 8-19-76

Flow Meas. Device Type Visi Float Serial No.: 002 Location: RTI Campus

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft^3/min)		
						Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	315	757	11.2	338	1.93	60.9	61.2	59.1
2	315	757	8.5	341	1.75	53.2	53.7	51.6
3	315	757	6.6	344	1.55	47.2	47.9	45.8
4	315	757	4.4	349	1.33	38.8	39.6	37.7
5	315	757	2.8	355	1.10	31.4	32.4	30.5

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
$Q_{theoretical} = 34.43 I - 5.78$ $r = .9988$	$Q_{theoretical} = 34.20 I - 7.47$ $r = .9988$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 8929 **Calibrator Type:** Orifice Cal. Unit **Date:** 8/19/76

Flow Meas. Device Type Visa Float **Serial No.:** 002 **Location:** RTI Campus

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft^3/min)		
						Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	305	763	11.3	329	1.90	60.0	61.7	59.4
2	305	763	8.9	331	1.75	53.4	55.1	52.9
3	305	763	7.0	334	1.55	47.6	49.3	47.1
4	305	763	4.4	341	1.38	38.1	39.9	37.7
5	305	763	2.8	347	1.08	30.8	32.5	30.5

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
$= 36.16 I - 7.70$ $r = .9924$	$= 35.84 I - 9.38$ $r = .9920$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 8929 Calibrator Type: Orifice Cal. Unit Date: 8/18/76

Flow Meas. Device Type Visa FloaT Serial No.: 002 Location: RTI Campus

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft³/min)		
						Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	296	760	11.6	318	1.90	59.9	62.3	60.1
2	296	760	9.1	320	1.75	53.3	55.6	53.5
3	296	760	6.7	324	1.50	46.0	48.3	46.1
4	296	760	4.4	328	1.30	37.6	39.7	37.7
5	296	760	2.6	333	1.00	29.3	31.2	29.4

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
$= 34.47I - 3.95$ $r = .9973$	$= 34.04I - 5.37$ $r = .9973$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 8929

Calibrator Type: Orifice Cal. UniT

Date: 8/18/76

Flow Meas. Device Type Visa FloaT

Serial No.: 002

Location: RTI Campus

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft^3/min)		
						Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	280	758	11.4	304	1.85	57.9	62.2	59.6
2	280	758	8.5	306	1.68	50.2	54.1	51.7
3	280	758	7.1	308	1.50	46.1	49.8	47.5
4	280	758	4.6	314	1.28	37.4	40.8	38.5
5	280	758	2.9	323	1.05	30.1	33.3	31.0

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
$= 35.51\ I - 4.24$ $r = .9970$	$= 35.21\ I - 6.16$ $r = .9971$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 8929 Calibrator Type: Orifice Cal. UniT Date: 8/26/76

Flow Meas. Device Type Visc. FloaT Serial No.: 002 Location: MounT MiTchell

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft^3/min)		
						Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	316	711	10.45	338	1.70	60.7	58.9	57.0
2	316	711	8.20	343	1.50	54.0	52.8	50.7
3	316	711	6.30	346	1.40	47.6	46.7	44.7
4	316	711	4.25	351	1.20	39.4	39.0	37.0
5	316	711	2.75	356	0.95	32.0	31.9	30.0

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
= 37.15I − 4.29 r = .9942	= 37.04I − 6.11 r = .9940

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 8929

Calibrator Type: Orifice Cal. UniT

Date: 8/26/76

Flow Meas. Device Type Visa FloaT

Serial No.: 002

Location: MounT MiTchell

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft^3/min) Q_a	Flow Rates (ft^3/min) $.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	Flow Rates (ft^3/min) $.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	306	711	10.1	329	1.70	58.8	58.1	56.1
2	306	711	8.1	331	1.50	52.9	52.5	50.5
3	306	711	6.3	332	1.40	46.8	46.5	44.7
4	306	711	4.7	337	1.20	40.7	40.7	38.8
5	306	711	2.25	343	0.95	28.7	29.0	27.4

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
$= 38.88 I - 7.13$ $r = .9949$	$= 38.37 I - 8.30$ $r = .9954$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 8929 Calibrator Type: Orifice Cal. UniT Date: 8/26/76

Flow Meas. Device Type Visa FloaT Serial No.: 002 Location: MounT MiTchell

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft^3/min) Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	297	711	10.6	319	1.90	59.3	59.5	57.4
2	297	711	8.3	322	1.70	52.7	53.1	51.0
3	297	711	6.3	325	1.50	46.2	46.8	44.7
4	297	711	4.2	327	1.35	38.0	38.6	36.8
5	297	711	2.5	336	1.00	29.7	30.6	28.8

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
$= 33.08 I - 3.58$ $r = .9922$	$= 32.77 I - 5.06$ $r = .9928$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 8929 Calibrator Type: Orifice Cal. UniT Date: 8/26/76

Flow Meas. Device Type Visa FlowT Serial No.: 002 Location: MounT MiTchell

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft^3/min)		
						Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	283	711	10.8	309	1.85	58.5	60.7	58.0
2	283	711	8.6	312	1.65	52.4	54.6	52.0
3	283	711	6.6	315	1.50	46.1	48.3	45.7
4	283	711	4.4	317	1.25	38.0	39.9	37.7
5	283	711	2.8	322	1.00	30.7	32.5	30.5

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
$= 33.73 I - 1.71$ $r = .9987$	$= 32.93 I - 2.97$ $r = .9986$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 1929 Calibrator Type: Orifice Cal. unit Date: 8/25/76

Flow Meas. Device Type Visa FlowT Serial No.: 002 Location: Mount Mitchell

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft³/min)		
						Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	315	633	9.6	336	1.65	61.6	56.5	54.7
2	315	633	7.3	341	1.50	53.9	49.8	47.8
3	315	633	6.0	345	1.35	49.0	45.5	43.5
4	315	633	3.9	346	1.10	39.9	37.1	35.4
5	315	633	2.3	354	0.80	31.0	29.2	27.5

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
$= 31.68I + 3.07$ $r = .9963$	$= 31.41I + 1.58$ $r = .9957$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 8929 Calibrator Type: Orifice Cal. UniT Date: 8/25/76

Flow Meas. Device Type VISA FloAT Serial No.: 002 Location: MounT MiTchell

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft^3/min) Q_a	Flow Rates (ft^3/min) $.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	Flow Rates (ft^3/min) $.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	305	633	9.4	330	1.70	60.0	56.2	54.1
2	305	633	7.4	331	1.55	53.5	50.2	48.3
3	305	633	5.7	332	1.40	47.1	44.3	42.5
4	305	633	3.8	340	1.15	38.8	36.9	35.0
5	305	633	2.2	346	0.95	30.0	28.8	27.1

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
$= 35.68I - 4.89$ $r = .9985$	$= 35.33I - 6.32$ $r = .9988$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 8929 Calibrator Type: Orifice Cal. uniT Date: 8/25/76

Flow Meas. Device Type Visa FloaT Serial No.: 002 Location: MounT MiTchell

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft^3/min)		
						Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	295	633	9.8	319	1.65	60.3	57.5	55.3
2	295	633	7.6	321	1.50	53.2	50.9	48.8
3	295	633	6.0	324	1.35	47.5	45.7	43.6
4	295	633	5.0	329	~~1.10~~	~~43.6~~	~~42.2~~	~~40.0~~ X
5	295	633	3.1	333	0.95	34.7	33.8	31.8

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
$= 33.16\ I + 1.79$ $r = .9960$	$= 32.91\ I - 0.04$ $r = .9961$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 8929 Calibrator Type: Orifice Cal. Unit Date: 8/25/76

Flow Meas. Device Type Visual Float Serial No.: 002 Location: Mount Mitchell

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft^3/min)		
						Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	281	633	10.00	306	1.70	59.4	58.3	55.8
2	281	633	8.20	308	1.55	54.0	53.2	50.7
3	281	633	6.30	310	1.40	47.5	46.9	44.6
4	281	633	4.20	314	1.15	39.1	38.9	36.7
5	281	633	2.50	320	0.90	30.6	30.7	28.8

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
$= 34.58\,I - 0.74$ $r = .9991$	$= 33.89\,I - 2.08$ $r = .9991$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 8929 Calibrator Type: Orifice Cal. UniT Date: 8/24/76

Flow Meas. Device Type Visa FloaT Serial No.: 002 Location: MounT MiTchell

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft^3/min) Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	316	596	9.20	341	1.65	62.2	55.6	53.5
2	316	596	7.20	344	1.40	55.3	49.6	47.5
3	316	596	5.80	347	1.20	49.8	44.2	42.8
4	316	596	4.40	348	1.00	43.6	39.4	37.5
5	316	596	2.90	355	0.85	35.7	32.6	30.7

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
$= 27.85\ I + 10.30$ $r = .9933$	$= 27.52\ I + 8.82$ $r = .9917$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 8929

Calibrator Type: Orifice Cal. Unit

Date: 8/24/76

Flow Meas. Device Type Visa Float

Serial No.: 002

Location: Mount Mitchell

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft^3/min)		
						Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	305	596	9.60	331	1.60	62.5	56.9	54.7
2	305	596	7.20	333	1.40	54.3	49.5	47.5
3	305	596	5.70	338	1.20	48.5	44.6	42.4
4	305	596	3.70	343	1.00	39.5	36.6	34.6
5	305	596	3.35	348	0.85			

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
$= 32.90I + 4.13$ $r = .9962$	$= 32.72I + 2.27$ $r = .9969$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 8929 Calibrator Type: Orifice Cal. UniT Date: 8/24/76

Flow Meas. Device Type Visc. FloaT Serial No.: 002 Location: MounT MiTchell

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft^3/min) Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	295	596	9.35	319	1.65	60.7	56.4	54.0
2	295	596	7.35	326	1.53	54.0	50.7	48.0
3	295	596	5.60	327	1.35	47.4	44.6	42.2
4	295	596	3.70	332	1.10	38.9	36.9	34.6
5	295	596	2.20	339	0.95	30.4	29.0	27.0

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
$= 37.21 I - 5.45$ $r = .9961$	$= 36.51 I - 6.86$ $r = .9960$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 8929 Calibrator Type: Orifice Cal.UniT Date: 8/24/76

Flow Meas. Device Type Visa. FloaT Serial No.: 002 Location: MounT MiTchell

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft³/min)		
						Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	285	596	9.00	311	1.61	58.6	55.4	53.0
2	285	596	7.60	316	1.50	54.0	51.5	48.9
3	285	596	5.80	319	1.35	47.4	45.4	42.9
4	285	596	3.40	320	1.10	36.7	35.2	33.2
5	285	596	2.25	331	0.90	30.2	29.5	27.3

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
$= 37.37I - 4.88$ $r = .9981$	$= 36.75I - 6.40$ $r = .9986$

APPENDIX B

ReF Device and Rotameter Calibration Data

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HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 8929 Calibrator Type: Ref device Date: 8/19/76

Flow Meas. Device Type Visa Float Serial No.: 103 Location: RTI Campus

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft^3/min)		
						Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	315	761	11.90	338	1.95	59.1	59.7	57.5
2	315	761	9.65	340	1.80	53.4	54.1	52.0
3	315	761	7.50	342	1.65	47.3	48.0	46.0
4	315	761	5.00	347	1.35	39.0	39.9	38.0
5	315	761	3.20	351	1.15	31.6	32.5	30.8

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
$= 33.18\ I - 5.58$ $r = .9977$	$= 32.60\ I - 6.64$ $r = .9978$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 8929
Calibrator Type: Ref device
Date: 8/19/76
Flow Meas. Device Type Visa Float
Serial No.: 103
Location: RTI Campus

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft^3/min)		
						Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	306	763	12.30	330	1.95	59.1	60.7	58.4
2	306	763	9.90	331	1.80	53.2	54.7	52.6
3	306	763	7.60	334	1.60	46.9	48.4	46.4
4	306	763	5.05	339	1.37	38.6	40.2	38.2
5	306	763	3.20	345	1.14	31.1	32.6	30.7

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
$= 34.43I - 6.81$ $r = .9996$	$= 34.01I - 8.20$ $r = .9997$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 8929 Calibrator Type: Ref device Date: 8/19/76

Flow Meas. Device Type Visa Float Serial No.: 103 Location: RTI Campus

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft^3/min)		
						Q_a	$.626\ Q_a \sqrt{\frac{P_b}{T_a}} \sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a \sqrt{\frac{P_b}{T_a}}$
1	296	767	12.60	319	1.88	58.7	61.3	59.2
2	296	767	10.20	322	1.76	53.0	55.7	53.4
3	296	767	7.80	324	1.58	46.6	49.1	47.0
4	296	767	5.20	328	1.34	38.4	40.7	38.7
5	296	767	3.25	334	1.11	30.8	32.9	31.0

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
$= 36.41 I - 7.91$ $r = .9988$	$= 36.03 I - 9.40$ $r = .9984$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 8929

Calibrator Type: Ref device

Date: 8/18/76

Flow Meas. Device Type Visa FloaT

Serial No.: 103

Location: RTI Campus

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft^3/min)		
						Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	284	759	12.88	311	1.84	58.5	62.6	59.9
2	284	759	10.45	311	1.69	52.9	56.6	54.2
3	284	759	7.95	314	1.50	46.4	49.9	47.7
4	284	759	5.95	317	1.31	40.4	43.7	41.3
5	284	759	3.35	323	1.08	30.8	33.6	31.5

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
$= 37.38 I - 6.19$ $r = .9987$	$= 36.76 I - 7.63$ $r = .9989$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 8929 Calibrator Type: Ref device Date: 8/26/76

Flow Meas. Device Type Visa Float Serial No.: 103 Location: Mount Mitchell

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft^3/min)		
						Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	316	711	11.20	345	1.87	59.4	58.3	55.8
2	316	711	9.15	345	1.75	53.9	52.9	50.6
3	316	711	6.55	347	1.53	45.9	45.1	43.1
4	316	711	4.80	350	1.38	39.6	39.1	37.2
5	316	711	3.05	355	1.14	31.9	31.7	30.0

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
$= 36.40 I - 10.42$ $r = .9983$	$= 35.32 I - 10.84$ $r = .9984$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 8929 Calibrator Type: RcF device Date: 8/26/76

Flow Meas. Device Type Visa FloaT Serial No.: 103 Location: MounT MiTchell

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft³/min)		
						Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	306	711	11.50	328	1.84	59.3	58.5	56.6
2	306	711	9.40	329	1.73	53.8	53.2	51.3
3	306	711	7.20	334	1.55	47.3	47.1	45.1
4	306	711	4.95	336	1.34	39.5	39.5	37.7
5	306	711	3.05	343	1.10	31.5	31.8	30.1

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
$= 35.63 I - 7.85$ $r = .9984$	$= 35.34 I - 9.27$ $r = .9982$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 8929   Calibrator Type: RcF device   Date: 8/26/76

Flow Meas. Device Type Visa Float   Serial No.: 103   Location: Mount Mitchell

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft^3/min)		
						Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	296	711	11.80	320	2.00	59.1	59.6	57.3
2	296	711	9.65	321	1.80	53.6	54.2	52.0
3	296	711	7.30	322	~~1.46~~	~~46.9~~	~~47.5~~	~~45.5~~
4	296	711	4.95	328	1.34	38.9	39.7	37.7
5	296	711	3.10	333	1.08	31.2	32.1	30.3

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
$= 30.23 I - 0.61$ $r = .9997$	$= 29.70 I - 1.87$ $r = .9997$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 8929

Calibrator Type: Ref device

Date: 8/26/76

Flow Meas. Device Type Visa FLoaT

Serial No.: 103

Location: MounT MiTchell

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft^3/min)		
						Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	287	711	12.30	310	1.88	59.3	60.8	58.4
2	287	711	10.00	313	1.78	53.7	55.3	52.9
3	287	711	7.65	316	1.60	47.2	48.8	46.5
4	287	711	5.25	318	1.40	39.4	40.9	38.8
5	287	711	3.20	327	1.15	31.2	32.8	30.7

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
$= 37.87 I - 11.43$ $r = .9974$	$= 37.38 I - 12.93$ $r = .9974$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 8929 Calibrator Type: Ref device Date: 8/25/76

Flow Meas. Device Type Visa FlowT Serial No.: 103 Location: MounT MiTchell

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft^3/min)		
						Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	316	633	10.7	343	1.80	61.5	56.7	54.5
2	316	633	8.5	345	1.69	55.0	50.9	48.7
3	316	633	6.6	348	1.56	48.7	45.2	43.1
4	316	633	4.4	355	1.34	40.2	37.7	35.6
5	316	633	3.7	359	1.10	37.0	34.9	32.8

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
$= 31.25 I - 1.73$ $r = .9703$	$= 31.09 I - 3.63$ $r = .9706$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 8929 Calibrator Type: Ref device Date: 8/25/76

Flow Meas. Device Type Visa. FlowT Serial No.: 103 Location: Mount Mitchell

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft^3/min)		
						Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	306	633	10.7	327	1.85	60.5	56.3	54.5
2	306	633	8.65	332	1.73	54.6	51.2	49.2
3	306	633	6.7	335	1.67	48.3	45.5	43.5
4	306	633	4.4	340	1.35	39.5	37.5	35.6
5	306	633	2.75	345	1.16	31.6	30.2	28.5

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
$= 36.02 I - 11.76$ $r = .9871$	$= 35.78 I - 13.28$ $r = .9859$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 8929 Calibrator Type: Ref device Date: 8/25/76

Flow Meas. Device Type Visa Float Serial No.: 103 Location: Mount Mitchell

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft^3/min)		
						Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	295	633	10.7	321	1.74	59.5	56.9	54.6
2	295	633	8.6	324	1.67	53.5	51.4	49.1
3	295	633	6.65	325	1.55	47.3	45.5	43.4
4	295	633	4.45	328	1.35	39.1	37.8	35.9
5	295	633	2.90	332	1.15	31.9	31.0	29.3

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
$= 42.49 I - 18.88$ $r = .9912$	$= 41.42 I - 19.34$ $r = .9906$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 8929

Calibrator Type: Ref device

Date: 8/25/76

Flow Meas. Device Type Visc. FloaT

Serial No.: 103

Location: Mount Mitchell

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft³/min)		
						Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	284	633	11.8	306	1.80	61.1	59.3	57.1
2	284	633	9.4	309	1.65	54.8	53.5	51.2
3	284	633	7.2	316	1.50	48.2	47.6	45.0
4	284	633	4.8	323	1.32	39.7	39.6	37.1
5	284	633	3.05	326	1.10	32.0	32.1	29.9

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
$= 39.41I - 11.66$ $r = .9992$	$= 39.47I - 14.11$ $r = .9987$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 8929 Calibrator Type: Ref device Date: 8/24/76

Flow Meas. Device Type Visa FloaT Serial No.: 103 Location: MounT MiTchell

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft^3/min) Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	318	596	10.2	343	1.80	62.0	55.2	53.1
2	318	596	7.9	348	1.62	54.8	49.2	47.0
3	318	596	6.25	349	1.56	49.0	44.0	42.0
4	318	596	4.2	354	1.32	40.5	36.6	34.7
5	318	596	2.7	363	1.08	32.9	30.2	28.2

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
$= 35.03I - 8.67$ $r = .9900$	$= 34.79I - 10.34$ $r = .9908$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 9929 Calibrator Type: Ref device Date: 8/24/76

Flow Meas. Device Type Visa FlowT Serial No.: 103 Location: MounT MiTchell

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft^3/min)		
						Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	306	596	9.9	330	1.75	60.0	54.4	52.4
2	306	596	7.6	332	1.69	52.8	48.0	46.1
3	306	596	6.15	334	1.52	47.7	43.5	41.7
4	306	596	4.2	344	1.30	39.8	36.8	34.8
5	306	596	2.6	349	1.05	31.7	29.6	27.7

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
$= 32.84I - 5.55$ $r = .9847$	$= 32.82I - 7.44$ $r = .9854$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 8929 Calibrator Type: Ref device Date: 8/24/76

Flow Meas. Device Type Visa Float Serial No.: 103 Location: Mount Mitchell

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft^3/min)		
						Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	297	596	10.1	323	1.83	59.8	55.3	53.0
2	297	596	8.1	324	1.69	53.7	49.8	47.6
3	297	596	6.3	327	1.5	47.6	44.3	42.2
4	297	596	4.2	333	1.28	39.2	36.8	34.8
5	297	596	2.7	339	1.02	31.9	30.2	28.3

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
$= 30.93I - 2.01$ $r = .9978$	$= 30.45I - 3.40$ $r = .9978$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 8929 Calibrator Type: Ref device Date: 8/24/76

Flow Meas. Device Type Visa Float Serial No.: 103 Location: Mount Mitchell

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft³/min)		
						Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	285	596	11.0	308	1.82	61.0	57.4	55.2
2	285	596	9.85	311	1.7	54.9	51.9	49.7
3	285	596	6.7	315	1.52	48.0	45.7	43.5
4	285	596	4.5	318	1.3	39.7	37.9	35.9
5	285	596	2.9	326	1.1	32.3	31.3	29.2

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
$= 35.82I - 8.46$ $r = .9989$	$= 35.59I - 10.26$ $r = .9989$

APPENDIX C

Orifice Calibration Unit and Pressure Transducer Calibration Data

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HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 7802 Calibrator Type: Orifice Cal. UniT Date: 8/19/76

Flow Meas. Device Type Pressure Transducer Serial No.: 002 Location: RTI Campus

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft^3/min)		
						Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	306	762	11.5	329	59.5	60.5	62.0	59.8
2	306	762	9.3	330	53.0	54.6	56.0	53.9
3	306	762	7.5	331	48.0	49.2	50.6	48.6
4	306	762	5.0	335	39.5	40.5	41.9	40.0
5	306	762	3.0	341	31.0	31.8	33.2	31.4

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
$= 1.019I + 1.730$ $r = .9998$	$= 1.004I - 0.328$ $r = .9998$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 7802 Calibrator Type: Orifice Cal. Unit Date: 8/18/76

Flow Meas. Device Type Pressure Transducer Serial No.: 002 Location: RTI Campus

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft^3/min)		
						Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	296	760	11.7	318	58.8	60.2	62.6	60.4
2	296	760	9.6	322	53.8	54.7	57.2	54.9
3	296	760	7.4	324	47.5	48.3	50.7	48.4
4	296	760	5.1	326	39.0	40.4	42.5	40.5
5	296	760	3.1	333	31.2	31.9	33.9	32.0

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
$= 1.029 I + 1.970$ $r = .9990$	$= 1.016 I + 0.462$ $r = .9996$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 7802 Calibrator Type: Orifice Cal. UniT Date: 8/18/76

Flow Meas. Device Type Pressure Transducer Serial No.: 002 Location: RTI Campus

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft^3/min)		
						Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	280	762	12.5	306	61.5	60.4	65.2	62.4
2	280	762	9.2	306	55.5	52.1	56.2	53.8
3	280	762	7.3	307	50.0	46.6	50.4	48.1
4	280	762	5.7	310	~~40.0~~	~~41.4~~	~~45.0~~	~~42.8~~
5	280	762	3.4	314	32.0	32.4	35.4	33.5

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
$= .936 I + 5.680$ $r = .9836$	$= .910 I + 4.611$ $r = .9870$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 7802 Calibrator Type: Orifice Cal. UniT Date: 8/25/76

Flow Meas. Device Type Pressure Transducer Serial No.: 002 Location: MounT MiTchell

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft^3/min)		
						Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	316	711	10.8	341	57.5	61.7	60.2	57.9
2	316	711	8.7	343	52.0	55.6	54.4	52.2
3	316	711	6.95	344	46.5	49.9	48.9	46.9
4	316	711	5.30	346	41.0	43.8	43.0	41.1
5	316	711	3.15	351	32.0	34.2	33.8	32.1

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
$= 1.035I + 0.647$ $r = .9999$	$= 1.011\ I - 0.271$ $r = .9999$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 7802 Calibrator Type: Orifice Cal. Unit Date: 8/26/76

Flow Meas. Device Type Pressure Transducer Serial No.: 002 Location: Mount Mitchell

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft^3/min)		
						Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	306	711	10.5	325	56.0	59.9	58.9	57.2
2	306	711	8.6	329	50.5	54.4	53.8	51.9
3	306	711	6.8	332	45.0	48.6	48.3	46.4
4	306	711	4.7	335	38.0	40.7	40.6	38.8
5	306	711	2.7	340	30.0	31.3	31.5	29.9

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
$= 1.058\ I + 0.174$ $r = .9992$	$= 1.052\ I - 1.361$ $r = .9995$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 7802 Calibrator Type: Orifice Cal. Unit Date: 8/26/76

Flow Meas. Device Type Pressure Transducer Serial No.: 002 Location: Mount Mitchell

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft^3/min)		
						Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	296	711	10.9	322	57.5	60.0	60.7	58.2
2	296	711	9.0	322	52.5	54.7	55.4	53.1
3	296	711	7.0	323	46.5	48.4	49.1	47.0
4	296	711	4.9	327	39.0	40.9	41.7	39.7
5	296	711	3.15	330	32.0	33.1	33.9	32.1

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
$= 1.043 I + .692$ $r = .9998$	$= 1.017 I - .263$ $r = .9999$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 7802 Calibrator Typ Orifice Cal. UniT Date: 8/26/76

Flow Meas. Device Type Pressure Transducer Serial No.: 002 Location: MounT MiTchell

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft³/min)		
						Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	283	711	11.10	309	58.5	59.3	61.5	58.8
2	283	711	9.15	309	52.5	54.0	56.0	53.6
3	283	711	7.20	311	46.5	48.1	50.0	47.7
4	283	711	4.90	314	38.8	40.0	41.8	39.7
5	283	711	3.25	317	31.2	32.9	34.6	32.6

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
$= .996\ I + 3.447$ $r = .9997$	$= .972\ I + 2.267$ $r = .9996$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 7802 Calibrator Type: Orifice Cal. unit Date: 8/25/76

Flow Meas. Device Type Pressure Transducer Serial No.: 002 Location: Mount Mitchell

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft^3/min)		
						Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	315	633	9.9	330	55.0	62.5	56.8	55.5
2	315	633	8.1	331	49.5	56.7	51.6	50.3
3	315	633	6.6	343	45.5	51.4	47.6	45.6
4	315	633	4.4	347	39.0	42.3	39.4	37.5
5	315	633	2.7	351	29.0	33.5	31.4	29.7

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
$=1.000I+1.758$ $r=.9969$	$=1.018I-0.669$ $r=.9959$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 7802 Calibrator Type: Orifice Cal. Unit Date: 8/25/77

Flow Meas. Device Type Pressure Transducer Serial No.: 002 Location: Mount Mitchell

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft^3/min)		
						Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	305	633	9.8	324	54.0	61.2	56.8	55.2
2	305	633	7.9	327	48.8	55.1	51.4	49.7
3	305	633	6.3	330	43.5	49.4	46.3	44.6
4	305	633	4.4	333	36.5	41.6	39.2	37.5
5	305	633	2.5	337	29.0	31.8	30.1	28.7

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
$= 1.056I + .016$ $r = .9990$	$= 1.049I - 1.296$ $r = .9993$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 7802 Calibrator Type: Orifice Cal. Unit Date: 8/25/76

Flow Meas. Device Type Pressure Transducer Serial No.: 002 Location: Mount Mitchell

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft^3/min)		
						Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	295	633	10.3	321	55.5	61.7	59.0	56.6
2	295	633	8.1	321	50.0	54.9	52.5	50.3
3	295	633	6.5	323	44.0	49.4	47.4	45.3
4	295	633	4.7	325	39.0	42.3	40.7	38.8
5	295	633	2.4	329	29.0	30.7	29.7	28.2

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
$=1.101 I - 2.037$ $r = .9987$	$=1.068 I - 2.612$ $r = .9988$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 7802 Calibrator Type: Orifice Cal. Unit Date: 8/25/76

Flow Meas. Device Type Pressure Transducer Serial No.: 002 Location: Mount Mitchell

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft^3/min) Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	282	633	10.4	308	56.0	60.6	59.4	56.8
2	282	633	8.5	308	50.5	55.0	53.9	51.6
3	282	633	6.6	309	45.0	48.7	47.8	45.7
4	282	633	5.2	312	39.5	43.4	42.8	40.7
5	282	633	3.0	315	30.0	33.4	33.1	31.3

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
= 1.011 I + 2.734 r = .9997	= .982 I + 1.806 r = .9998

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 7802 Calibrator Type: Orifice Cal. UniT Date: 8/24/76

Flow Meas. Device Type Pressure Transducer Serial No.: 002 Location: MounT MiTchell

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft^3/min) Q_a	Flow Rates (ft^3/min) $.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	Flow Rates (ft^3/min) $.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	316	596	9.5	341	53.5	63.2	56.5	54.3
2	316	596	7.5	342	48.5	56.3	50.4	48.4
3	316	596	5.7	344	43.0	49.4	44.3	42.5
4	316	596	4.8	347	38.5	45.4	40.9	39.0
5	316	596	2.7	351	29.0	34.5	31.3	29.7

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
$= 1.012 I + 1.654$ $r = .9979$	$= .990 I + 0.698$ $r = .9993$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 7802 Calibrator Type: Orifice Cal. UniT Date: 8/24/76

Flow Meas. Device Type Pressure Transducer Serial No.: 002 Location: MounT MiTchell

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft^3/min)		
						Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	306	596	10.2	329	54.0	64.4	58.4	56.3
2	306	596	8.7	331	48.5	59.6	54.2	52.1
3	306	596	5.9	332	43.0	49.4	45.0	43.2
4	306	596	4.1	337	36.0	41.5	38.1	36.3
5	306	596	2.7	341	29.8	40.0	36.9	35.0

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
$= .965I + 5.727$ $r = .9730$	$= .954I + 4.259$ $r = .9748$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 7802 Calibrator Type: Orifice Cal. Unit Date: 8/24/76

Flow Meas. Device Type Pressure Transducer Serial No.: 002 Location: Mount Mitchell

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft^3/min)		
						Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	296	596	10.0	322	55.0	62.8	58.2	55.8
2	296	596	7.8	322	49.0	55.6	51.5	49.4
3	296	596	6.1	325	43.5	49.4	46.0	43.9
4	296	596	4.9	327	38.0	44.3	41.3	39.4
5	296	596	2.6	333	28.5	32.9	31.0	29.2

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
$= 1.011I + 2.316$ $r = .9993$	$= .990I + 1.174$ $r = .9992$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 7802 Calibrator Type: Orifice Cal. UniT Date: 8/24/76

Flow Meas. Device Type Pressure Transducer Serial No.: 002 Location: MounT MiTchell

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft^3/min) Q_a	Flow Rates (ft^3/min) $.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	Flow Rates (ft^3/min) $.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	282	596	10.3	305	55.8	62.2	58.9	56.6
2	282	596	8.1	306	49.9	55.4	52.5	50.4
3	282	596	6.3	309	43.0	49.1	46.8	44.7
4	282	596	5.4	312	36.5	45.5	43.6	41.4
5	282	596	2.8	315	29.5	33.3	32.0	30.3

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
$= .952 I + 5.902$ $r = .9833$	$= .935 I + 4.541$ $r = .9853$

APPENDIX D

ReF Device and Pressure Transducer Calibration Data

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 7802 Calibrator Type: Ref device Date: 8/19/76

Flow Meas. Device Type Pressure Transducer Serial No.: 103 Location: RTI Campus

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft^3/min)		
						Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	313	762	11.2	335	59.0	60.5	61.1	59.1
2	313	762	9.1	338	53.0	54.7	55.5	53.4
3	313	762	7.3	340	47.0	49.2	50.1	48.1
4	313	762	5.0	344	39.0	41.0	42.0	40.0
5	313	762	3.0	348	31.0	32.3	33.3	31.5

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
	$= .982 I + 1.427$ $r = .9994$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 7802 Calibrator Type: Ref device Date: 8/19/76

Flow Meas. Device Type Pressure Transducer Serial No.: 103 Location: RTI Campus

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft^3/min)		
						Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	305	763	12.5	327	61.0	59.6	61.1	59.0
2	305	763	10.35	329	56.5	54.4	55.9	53.9
3	305	763	8.25	331	51.5	48.8	50.3	48.3
4	305	763	5.7	334	43.5	40.9	42.4	40.5
5	305	763	3.8	337	36.3	33.7	35.1	33.4

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
	$= .989I + .051$ $r = .9999$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 7802 Calibrator Type: Ref device Date: 8/18/76

Flow Meas. Device Type Pressure Transducer Serial No.: 103 Location: RTI Campus

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft^3/min) Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	296	760	12.70	319	60.8	59.2	61.6	59.4
2	296	760	10.60	320	56.2	54.3	56.6	54.5
3	296	760	9.00	321	51.0	50.2	52.4	50.4
4	296	760	5.75	325	41.5	40.5	42.6	40.6
5	296	760	3.85	329	36.0	33.5	35.4	33.6

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
	$= 1.021 I - 2.415$ $r = .9980$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 7802
Calibrator Type: Ref device
Date: 8/18/76
Flow Meas. Device Type Pressure Transducer
Serial No.: 103
Location: RTI Campus

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft^3/min)		
						Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	287	760	13.25	310	61.0	59.5	63.0	60.6
2	287	760	11.0	312	55.8	54.4	57.8	55.4
3	287	760	8.75	313	50.0	48.7	51.8	49.6
4	287	760	5.95	317	41.5	40.5	43.4	41.3
5	287	760	4.1	319	35.0	33.9	36.4	34.5

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
	$= 1.000I - 0.373$ $r = .9999$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 7802 Calibrator Type: Ref device Date: 8/26/76

Flow Meas. Device Type Pressure Transducer Serial No.: 103 Location: MounT MiTchell

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft³/min)		
						Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	316	711	12.0	339	57.9	64.9	63.1	60.9
2	316	711	9.85	341	53.0	59.0	57.6	55.4
3	316	711	7.90	342	47.5	53.1	51.9	49.9
4	316	711	5.35	345	40.04	44.0	43.2	41.3
5	316	711	3.30	352	32.0	35.0	34.7	32.9

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
	$= 1.083 I - 1.822$ $r = .9998$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 7802 Calibrator Type: Ref device Date: 8/26/76

Flow Meas. Device Type Pressure Transducer Serial No.: 103 Location: Mount Mitchell

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft^3/min)		
						Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	306	711	12.0	330	58.1	60.4	59.8	57.6
2	306	711	10.1	331	53.5	55.6	55.1	53.1
3	306	711	7.9	332	48.0	49.4	49.1	47.1
4	306	711	6.65	335	41.0	45.5	45.4	43.4
5	306	711	3.6	340	33.0	34.0	34.2	32.4

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
	$= .962I + 1.766$ $r = .9909$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 7802 Calibrator Type: Ref device Date: 8/26/76

Flow Meas. Device Type Pressure Transducer Serial No.: 103 Location: MounT Mitchell

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft³/min)		
						Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	297	711	11.95	319	59.0	59.4	59.6	57.5
2	297	711	10.0	320	53.5	54.5	54.8	52.8
3	297	711	7.95	322	49.2	48.8	49.2	47.3
4	297	711	5.50	327	42.0	41.0	41.7	39.7
5	297	711	3.06	331	34.9	31.1	31.8	30.1

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
	$= 1.142I - 8.991$ $r = .9975$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 7802 Calibrator Type: Ref device Date: 8/26/76

Flow Meas. Device Type Pressure Transducer Serial No.: 103 Location: Mount Mitchell

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft^3/min)		
						Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	286	711	12.15	309	60.05	58.9	60.4	58.1
2	286	711	10.2	310	55.9	54.1	55.6	53.4
3	286	711	8.05	312	50.5	48.3	49.8	47.7
4	286	711	5.7	314	43.2	41.0	42.4	40.5
5	286	711	3.5	319	35.5	32.5	33.9	32.1

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
	$= 1.049 I - 5.067$ $r = .9998$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 7802 Calibrator Type: Ref device Date: 8/25/76

Flow Meas. Device Type Pressure Transducer Serial No.: 103 Location: Mount Mitchell

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft^3/min)		
						Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	317	633	10.50	339	55.5	60.9	55.7	53.9
2	317	633	8.80	342	51.2	56.0	51.5	49.5
3	317	633	7.00	345	45.0	50.1	46.2	44.3
4	317	633	4.90	349	38.5	423	39.3	37.4
5	317	633	3.35	353	32.1	35.3	33.0	31.2

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
	$= .967I + 0.277$ $r = .9994$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 7802 Calibrator Type: Ref device Date: 8/25/76

Flow Meas. Device Type Pressure Transducer Serial No.: 103 Location: Mount Mitchell

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft^3/min)		
						Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	307	633	11.05	331	56.0	61.5	57.4	55.3
2	307	633	9.25	333	51.5	56.5	52.9	50.8
3	307	633	7.30	334	46.2	50.4	47.3	45.3
4	307	633	5.00	338	39.0	42.0	39.6	37.8
5	307	633	3.20	344	32.0	34.0	32.4	30.6

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
	$= 1.032I - 2.412$ $r = .9999$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 7802 Calibrator Type: Ref device Date: 8/25/76

Flow Meas. Device Type Pressure Transducer Serial No.: 103 Location: Mount Mitchell

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft^3/min)		
						Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	296	633	11.45	318	55.8	61.5	58.4	56.3
2	296	633	9.50	321	51.5	56.2	53.6	51.4
3	296	633	7.50	324	46.0	50.1	48.0	45.9
4	296	633	5.15	327	38.0	41.9	40.3	38.4
5	296	633	3.35	331	30.1	34.2	33.1	31.3

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
	$= .966\ I + 1.896$ $r = .9992$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 7802 **Calibrator Type:** Ref device **Date:** 8/25/76

Flow Meas. Device Type Pressure Transducer **Serial No.:** 103 **Location:** Mount Mitchell

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft^3/min)		
						Q_a	$.626\, Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\, Q_a\sqrt{\frac{P_b}{T_a}}$
1	285	633	11.7	307	57.0	61.0	59.1	56.9
2	285	633	9.65	308	53.5	55.6	54.0	51.9
3	285	633	7.70	310	47.0	49.9	48.6	46.6
4	285	633	5.20	313	39.0	41.3	40.4	38.5
5	285	633	3.45	319	32.0	34.0	33.6	31.7

$.626\, Q_a\, [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\, Q_a(P_b/T_a)^{1/2}$ on I
	$= .984I + .410$ $r = .9984$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 7802 Calibrator Type: Ref device Date: 8/24/76

Flow Meas. Device Type Pressure Transducer Serial No.: 103 Location: MounT MiTchell

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft^3/min)		
						Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	317	596	10.70	340	53.9	63.4	56.4	54.4
2	317	596	8.75	342	50.0	57.6	51.4	49.4
3	317	596	6.85	344	44.5	51.1	45.7	43.9
4	317	596	4.80	349	37.4	43.1	38.8	37.0
5	317	596	3.10	354	30.5	35.1	31.8	30.1

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
	$=1.022I - 1.267$ $r = .9991$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 7802 Calibrator Type: Ref device Date: 8/24/76

Flow Meas. Device Type Pressure Transducer Serial No.: 103 Location: Mount Mitchell

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft^3/min)		
						Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	306	596	10.70	331	55.5	62.3	56.6	54.4
2	306	596	8.85	334	50.5	56.9	51.9	49.7
3	306	596	7.00	335	45.0	50.8	46.4	44.4
4	306	596	4.80	339	38.0	42.4	39.0	37.0
5	306	596	3.15	344	31.5	34.7	32.1	30.3

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
	$= 1.008 I - 1.302$ $r = .9997$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 7802 Calibrator Type: Ref device Date: 8/24/76

Flow Meas. Device Type Pressure Transducer Serial No.: 103 Location: Mount Mitchell

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft³/min)		
						Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	297	596	10.95	320	55.5	62.2	57.3	55.2
2	297	596	9.20	323	51.2	57.1	52.8	50.6
3	297	596	7.25	324	46.0	51.0	47.2	45.2
4	297	596	4.90	328	34.7	42.2	39.3	37.4
5	297	596	3.15	333	31.5	34.3	32.2	30.4

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
	$= 1.031 I - 2.123$ $r = .9999$

HI-VOLUME SAMPLER CALIBRATION DATA SHEET

Hi-Volume Sampler No. 7802 Calibrator Type: Ref device Date: 8/24/76

Flow Meas. Device Type Pressure Transducer Serial No.: 103 Location: MounT Mitchell

Run No.	Ambient Temp. T_a (°K)	Barometric Pressure P_b (mm Hg)	Pressure Drop Across Calibrator ΔH (in H_2O)	Exhaust Temp. T_e (°K)	Flow Rate Indication I (Arbitrary)	Flow Rates (ft^3/min)		
						Q_a	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}\sqrt{\frac{T_e}{T_a}}$	$.626\ Q_a\sqrt{\frac{P_b}{T_a}}$
1	286	596	11.25	309	56.0	61.8	58.1	55.8
2	286	596	9.20	311	51.5	56.1	52.9	50.7
3	286	596	7.30	313	46.5	50.2	47.5	45.4
4	286	596	4.95	316	39.0	41.7	39.6	37.7
5	286	596	3.35	320	32.5	34.6	3.3.1	31.3

$.626\ Q_a\ [(P_b/T_a)(T_e/T_a)]^{1/2}$ on I	$.626\ Q_a(P_b/T_a)^{1/2}$ on I
	$=1.040I - 2.712$ $r = .9997$